Journal of Applied Biology & Biotechnology 2025. Article in Press
Available online at http://www.jabonline.in
DOI: 10.7324/JABB.2026.244399

Genetically modified crops: Advances, biosafety, and the quest for sustainable food

Satyajit Saurabh*

DNA Fingerprinting Laboratory, Bihar State Seed and Organic Certification Agency, Patna, Bihar, India.

ARTICLE INFO

Article history:
Received on: 24/02/2025
Accepted on: 05/07/2025
Available online: ***

Key words:
Crop improvement,
Biotechnology,
Biosafety,
Biosecurity,
Environment,
Regulations.

ABSTRACT

Since antiquity, humans have been highly influenced by genetic makeup for crop selection and its domestication through selective breeding and mutation breeding. Novel crosses for modifying the genetic makeup to produce hybrids with the beneficial trait(s) are started by traditional crop breeders. Further, the alterations in genetic makeup are introduced by mutations and plant tissue culture. Now, the modern biotechnological strategies enable gene(s) transfer between species, for genomic manipulation, which could not occur naturally. Genetic manipulation results in producing genetically modified (GM) crops with beneficial traits, including quality improvement, increased yield, and stress tolerance. As GM crops should be safe for consumption and the environment, GM produce, as a whole crop, crop part, or processed food, has to be considered for an early safety evaluation. Because the biotechnology involved in genetic manipulation may bring some known and unknown risks. As per our knowledge at present, there are three categories of potential risks related to the use of modern biotechnology: (i) risks related to the health of humans, animals, and plants, (ii) risks related to the protection of biodiversity and agricultural sustainability, and (iii) risks related to the ethical and socioeconomic issues. With all-new strategies and technologies, several doubts, questions, and concerns are being raised about tampering with Mother Nature and the associated risks to the environment and consumer health. This review aims to address several key issues associated with recombinant technology and GM foods, such as biosafety, ecological and environmental concerns, and health risks.

1. INTRODUCTION

The UN estimates that there will be 9.7 billion people on the planet in 2050, which will make feeding them a tremendous challenge. The growing population across the globe, particularly in developing countries, raises the demand for an increase in food production by 70% by the year 2050 [1]. To feed the growing population, genetic manipulation(s) has to be utilized for sustainably enhancing agricultural produce to meet the increasing demand for food, feed, and fiber [2]. Conventional plant breeding technologies have been utilized for generations to produce improved crops or to produce new crops, by the change in chromosome numbers, induced mutations, and tissue culture (somatic embryogenesis and embryo rescue to recover sterile offspring) [3,4]. Then, with the discovery of DNA transfer between organisms in the 1970s, genetically modified (GM) tobacco plants were first produced in 1983 and commercialized in the early 1990s, followed by the transgenic “Flavr Savr tomato.” This has encouraged the development, introduction, and rapid adoption of highly successful GM varieties of rice, tomato, mushroom, soybeans, cotton, corn, and canola. The year-wise timeline of remarkable milestones is tabulated in Table 1.

The plants are being GM to gain the trait(s) for stress (biotic and abiotic) tolerance to enhance the level of crop protection for increased crop yield. The likelihood that GM cultivars of small-acreage crops will be developed and widely adopted, however, is unclear. The GM crops developed through genetic engineering are in queue for approval from the biosafety-related regulatory authorities to be commercialized. Although the consumer acceptance of GM micro-organisms is being accepted for pharmaceuticals, etc., when it comes to GM crops, a multifactorial rejection is being seen in commercialization for agriculture-based food products. With such negative public perception, opinion, and sensitivity, GM food has been on hold. Often acknowledged as a vital component of the global food supply, GM foods are associated with Sustainable Development Goal (SDG) 2: No hunger. Nevertheless, a number of the advantages and disadvantages of eating GM crops are still unclear [5].

Advancements in biotechnology offer promising solutions for improving food production and sustainability. However, to realize their full potential, it is essential to address the accompanying challenges and concerns, ensuring that these technologies are developed and implemented responsibly, ethically, and equitably to promote a sustainable food supply for all. The basic challenges and concerns

*Corresponding Author:
Satyajit Saurabh, DNA Fingerprinting Laboratory, Bihar State Seed and Organic Certification Agency, Patna, Bihar, India. E-mail: satyajitsaurabh@gmail.com; satyajit.agri@bihar.gov.in

Table 1: The year-wise timeline of remarkable milestones in molecular biology.

Year	Description of remarkable milestones
Circa 8000 BCE	Humans use traditional mod methods like selective breeding and cross-breeding to bred plants & animals with more desirable traits.
1859	Charles Darwin published "On the Origin of Species"
1866	Gregor Mendel breeds two types of peas & identifies basic process of genetics.
1869	Frederick Miescher isolated DNA
1902	Walter Sutton developed chromosome theory of inheritance
1911	Thomas Hunt Morgan showed chromosomes carry genes
1922	First hybrid corn is produced & sold commercially.
1940	Plant breeders learn to use radiations or chemicals to randomly change an organism's DNA.
1944	Oswald Avery *et al*. demonstrated DNA can transform the properties of cells
1946	Scientists discovered DNA transfer between organisms.
1953	The discoveries of DNA structure by chemist Rosalind Franklin, scientists James Watson & Francis crick.
1973	Biochemists Herbert Boyer & Stanley Cohen develops genetic engineering by inserting DNA from one bacterium into another. It involves "cutting and pasting" using restriction endonucleases (molecular scissors) and DNA ligase (glue).
1982	U.S.FDA approves the first consumer GMO product developed through genetic – engineering human insulin to treat diabetes.
1983	The antibiotic-tobacco plant is produced as first GM plant.
1986	The federal government establishes the coordinated framework for the co-ordination of U.S. FDA, U.S. EPA & U.S.DA for biosafety regulation related to GMOs.
1992	U.S.FDA policy states that GM foods must meet the safety standards similar to food derived from traditionally bred crop plants.
1994	First GMO produce created through genetic engineering - a Flavr savr (Flavour Saver) tomato - proved safe after evaluation by federal agencies – available commercially.
1990s	China was the first country to commercialize a GM crop, virus-resistant tobacco. The first wave of GMO produced through commercial availability of genetically engineered summer squash, soybeans, cotton, corn, papayas, tomatoes, potatoes, & canola. However, some crops are lifted from sale at present.
2002	Bt cotton introduced in India. This is based on single-gene technology and approved for commercialization.
2003	WHO & FAO develop International guidelines & standards to determine the biosafety of GMO & derived foods.
2005	GMO alfalfa & sugar beets are available for sale in the US.
2006	GEAC approved commercialization of next-generation Bt cotton, having double-gene technology (Cry1Ac and Cry2Ab)
2006	Activists filed a PIL against GM crops in the Supreme Court of India.
2007	GEAC granted approval for import of refined soybean oil derived from glyphosate-tolerant soybeans.
2007	GEAC recommended commercial release of Bt brinjal. It is developed by Mahyco in collaboration with UAS, Dharwad and TNAU.
2010	The then environmental minister Jairam Ramesh blocked the release of Bt Brinjal until further notice owing to a lack of consensus among scientists and opposition from brinjal – growing states.
2012	In India, the Parliamentary Standing Committee on agriculture, in 37th report asked for an end to all GM field trials in the country.
2013	The panel of Supreme Court of India suggested moratorium on GM trials – No official verdict. The Environment Minister, Jayanthi Natarajan holds all trials.
2014	The Environment Minister, Veerappa Moili cleared the way for trials in one - acre.
2014	GEAC approved field trials for 11 crops including maize, rice, sorghum, wheat, groundnut and cotton.
2014	GEAC approved 21 new varieties for field trials including rice, wheat, groundnut and cotton.
2014	GEAC approved import of oil processed from herbicide-tolerant soybean and canola.
2015	USPDA approves – genetic modifications in salmon (animal) for use as food.
2016	Congress passes a law – required to label the foods product the genetic engineering as bioengineered food.
2016	GEAC gave green signal to GM mustard for field trial.
2017	Media reported unapproved GM events in several states of India. Department of Biotechnology instituted Field Inspection and Scientific Evaluation Committee (FISEC) to ascertain such unapproved cultivation and production of GMOs.
2017	GEAC recommended allowing environmental release for GM mustard. The GM mustard (Dhara Mustard Hybrid 11 or DMH 11) is herbicide tolerant, developed by the Centre for Genetic Manipulation of Crop Plants, Delhi University using "barnase/bartar" technology
2017	GMO apples are available for sale in the US.
2018	GEAC approved field studies on GM mustard for honeybees and other pollinators.

(Contd...)

Table 1: *(Continued).*

Year	Description of remarkable milestones
2019	Illegal Bt Brinjal cultivation in one of the Northern State of India, Haryana.
2019	GM Satyagraha was observed in Maharashtra State of India. A farmers' organization was launched a full-fledged protest by sowing HTBt Cotton seeds, illegally after ban.
2019	USFDA completes consultation on first food from a genome edited plant – high oleic soybean oil.
2020	GEAC has allowed biosafety research field trials for two new transgenic varieties of Bt Brinjal in eight states during 2020-23.
2022	Government of India relaxes rules around gene-edited crops on March 30.
2024	Government of India approved the proposal '**BioE3** (Biotechnology for Economy, Environment and Employment) **Policy for Fostering High Performance Biomanufacturing**' of the Department of Biotechnology.
2025	The Supreme Court of India ordered the government to formulate a national policy for GM crops based on science to address research, cultivation, trade, and commerce; which prioritizes climate adaptation, agricultural productivity, and reducing dependence on imported oils and pulses.

GM: Genetically modified, GMO: Genetically modified organism, GEAC: Genetic engineering appraisal committee, WHO: World Health Organization, FAO: Food and Agriculture Organization, EPA: U.S. Environmental Protection Agency.

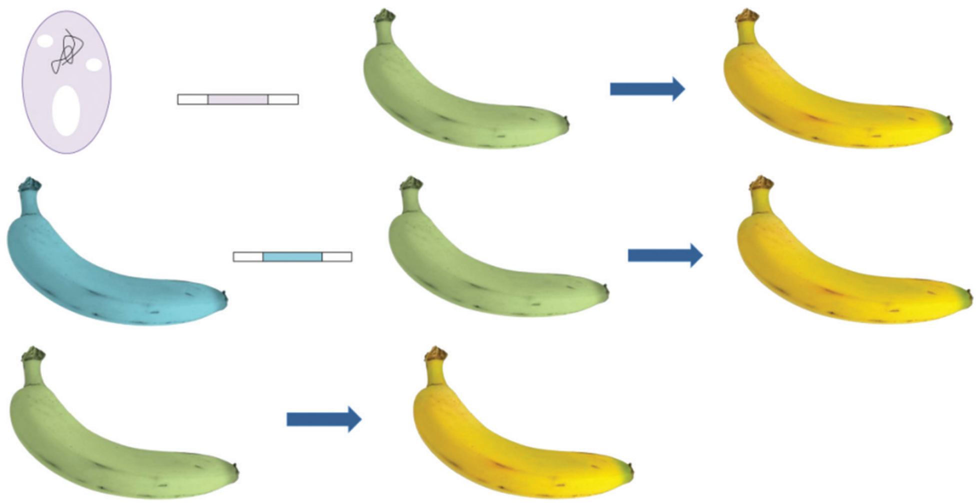

Figure 1: The diagrammatic illustration of strategies utilized in genetic modifications for crop improvement. (a) Genes from a different (sexually incompatible) species are injected into transgenic plants. (b) Genes from the same species or a closely related one, where conventional plant breeding is possible, are used to create cisgenic plants. (c) To modify a plant's genetic makeup without introducing genes from other plants, intragenic/subgenic plants are created utilizing gene knockdown or gene knockout techniques.

associated with genetic modification techniques are Regulatory Hurdles (potentially hindering innovation), Public Perception and Acceptance (regarding health, safety, and environmental impacts), Intellectual Property Issues (affecting smallholder/marginal farmers for equitable access to technology), and Biodiversity Concerns (genetic uniformity may create crops vulnerable to new pests and diseases). The concerns, such as environmental impact, socioeconomic implications, ethical considerations, consumer perceptions, and food security and accessibility, are reviewed for Sustainable Food Supply. This article is an attempt to address the efforts among scientists, policymakers, and stakeholders for fostering an environment conducive to innovations for crop improvement with the objective of "SDG2: No Hunger" while safeguarding health, environment, and social equity.

2. MODERN BIOTECHNOLOGY

The discipline of biotechnology is defined by the Convention on Biological Diversity (CBD) as any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use. Biotechnology is being integrated with other disciplines (like nanotechnology) to accelerate research-based studies and applications. At the same time, the new approach and possibility of creating and/or modifying the life forms may encounter biotechnological abuse, risks, and challenges. This creates the necessity of biosafety to address the biological risks by (i) the real-time monitoring and early warning system, (ii) the identification, prevention, and control, and (iii) the emergency measures to counter the risks.

Biotechnology is being considered a powerful tool of science to feed the future. In the last four decades, the discipline of biotechnology has been rapidly developing and utilized in the field of life sciences. The use of modern biotechnology involves recombinant DNA technology in crop improvement. This has been adopted for broad scope, precise genetic changes, and faster results [6]. Three strategies of genetic manipulations are involved in genetic modifications, namely, transgenesis, cisgenesis, and intragenesis/subgenesis [Figure 1]. The progress of tools utilized in the modification of DNA for genetic manipulations is illustrated in Figure 2. These tools are being proven as novel approaches to combating stress and improving nutritional attributes.

GMO can be defined as any living organism that has been manipulated artificially at the level of its genome. GM plants are being developed and cultivated for the increase in food and fodder, with other desirable traits. Moreover, the foods derived from such GM crop plants are referred to as

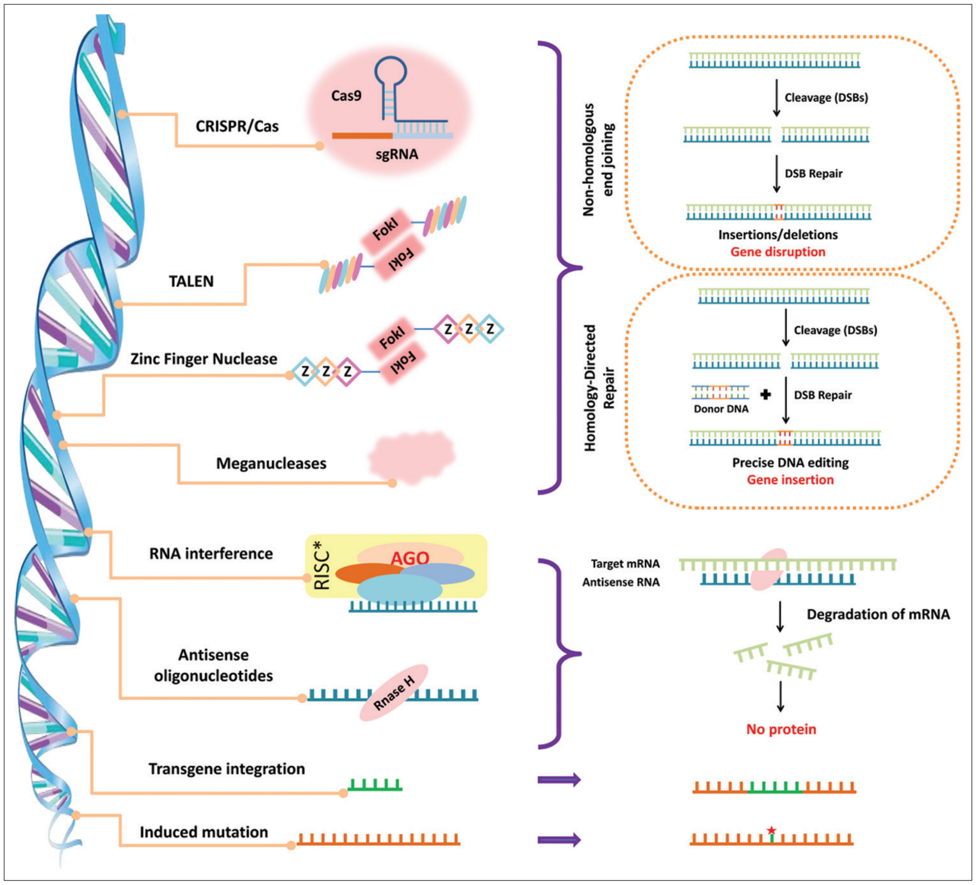

Figure 2: Progress of biotechnological tools utilized for genetic manipulations.

GM foods. GM foods are being produced to meet the desires of producers and/or consumers in terms of yield, shelf life, and nutritional benefits. The development and production of GM crops and derived foods are progressing in many countries such as India, China, the USA, Brazil, Argentina, and Canada but it is not promoted and accepted significantly in various other countries [7]. The majority of today's GMO crops were created to assist farmers in avoiding crop loss. In GMO crops, the three most prevalent characteristics are: Resistance to harm by insects, herbicide tolerance, and plant virus resistance.

The modern era of plant breeding via mutagenesis was brought about by the discovery and use of targetable site-directed nuclease (SDN) enzymes, as strong instruments for precisely manipulating crop genomes (commonly referred to as "gene editing"), typically using RNA-guided CRISPR-Cas technology, dominated the field since 2013. The SDN can be applied in three different ways, which could lead to end products that are subject to different rules. SDN1–the most widely used SDN technique in plants to date–is the recovery of plants with specified mutations that arise solely from the random non-homologous end joining repair mechanism of the cell without a donor template. The majority of these edits are insertions or deletions that take place in the vicinity of the double-stranded DNA break. While both SDN2 and SDN3 plants use the homology-directed repair procedure and a provided repair template, the extent of the induced change varies [7,8].

3. BIOSAFETY: MEASURES, ASSESSMENT, AND REGULATIONS

The genetic alterations could be passed down through generations and could have unfavorable consequences that pose a risk to biosafety. The modified gene(s) may be transferred into natural plant populations as a result of natural breeding between the modified agricultural plants and their nearby wild relatives. As any wild recipient of such a gene may have a competitive advantage in natural ecosystems, such an occurrence could threaten biodiversity. Such a transplanted gene can stay unexpectedly longer in the environment and produce products that have an impact on non-target species, volunteer plants, and the environment.

The associated risks for the assessment procedure are tabulated in Table 2. The risk assessment could be carried out by considering (i) Random gene insertion, which may cause insertional mutagenesis, which alters or suppresses the expression of the native endogenous genes in host plant; (ii) The activation of silent genes and upregulation of down-regulated/low expressed genes, which may cause a change in biochemical pathways and produce undesired secondary compounds that may be toxic or allergenic in nature; (iii) The downregulation of housekeeping gene, which may cause low or no production of essential compounds – life-threatening, reduced/altered nutritional quality; and (iv) Although no report is published till date showing major health concerns with GM foods, does not mean to believe that everything is OK with GM foods [9].

At the Rio de Janeiro Earth Summit in 1992, world leaders adopted a comprehensive plan for "sustainable development," which aims to address human needs for health, the environment, and biodiversity while preserving the planet for future generations. The CBD), which established three main objectives–the conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of the benefits resulting from the use of genetic

Table 2: The risks considered for the assessment procedure during GM crop development.

Spread and escape of GM crop plants in the environment through
(i) Reproductive isolation
(ii) Spatial isolation
(iii) Temporal isolation
(iv) Destroying the vectors carrying modified gene(s), i.e., GMMOs or GM plants
(v) Preventing the dissemination and germination of seeds produced in GM plants
Survival, life tenure, and fecundity of GM crops in open environments (niche)
Expression of modified gene(s) and its effect on
(i) The physiology, biochemistry, and morphology of GM crop plant
(ii) The feeding organism in terms of nutrition, toxicity, and/or allergenicity
(iii) The interacting species and the ecosystem
Unintended expression(s) of manipulated/modified gene(s)
Unintended effect on flora and fauna in the cultivated area
Transfer of modified gene(s) as hybridization and introgression to
(i) Feral and wild relatives
(ii) Sexually compatible species
(iii) Other species as horizontal gene transfer
Advantage or disadvantage associated with the stability and loss of
(i) Phenotype in the following generations
(ii) Genotype in the following generations
Direct and indirect implications associated with the interaction of GM crops and the environment, such as
(i) Soil composition, health, and texture
(ii) Soil-inhabiting organisms
(iii) Ecology and biodiversity
(iv) Food web

resources–was one of the major agreements adopted at Rio. The CBD's Article 28 allows for the creation of Protocols to address the execution of different sections of the Agreement.

The use of modern biotechnology is a developing international concern due to the need to protect human health and the environment from potential negative consequences. Recognizing modern biotechnology's ability to meet the urgent global demands for food and healthcare is crucial, nevertheless. In response to these concerns, the Conference of the Parties to the CBD enacted the Cartagena Protocol on Biosafety (CPB) on January 29, 2000, in Montreal (https://www.cbd.int/doc/legal/cartagena-protocol-en.pdf; accessed on 03 June 2025). The CPB includes provisions to regulate, manage, or control risks related to the movement of organisms and products derived from modern biotechnology across international borders that may have an adverse impact on the conserving and sustainable use of biological diversity [10,11]. There is a necessity to monitor for assessment and evaluation of potential risks as biosafety requirements during the entire process of GM crop development and its commercial release [Figure 3].

The early research for the development of GM plants has to be performed with special consideration of containment in confined structures such as designated laboratories and/or greenhouses. The personnel associated with such research must have standard operating procedures and a reference manual for biosafety and good laboratory practices. The evaluation-based study has to be performed as a field trial to ensure the prevention of dissemination/escape of gene(s) in the environment/food chain. The data relating to potential agronomic benefits, environmental risk assessment, and food safety assessments have to be collected. Finally, the commercial release of a GM crop at different geographical locations in a variety of environments, with an assumption of negligible and/or manageable risks. The GM plants may give direct, indirect, immediate, or delayed, unpredictable effects [Figure 4]. The post-release monitoring activity has to be planned to reassess the evaluation of agronomic performances and

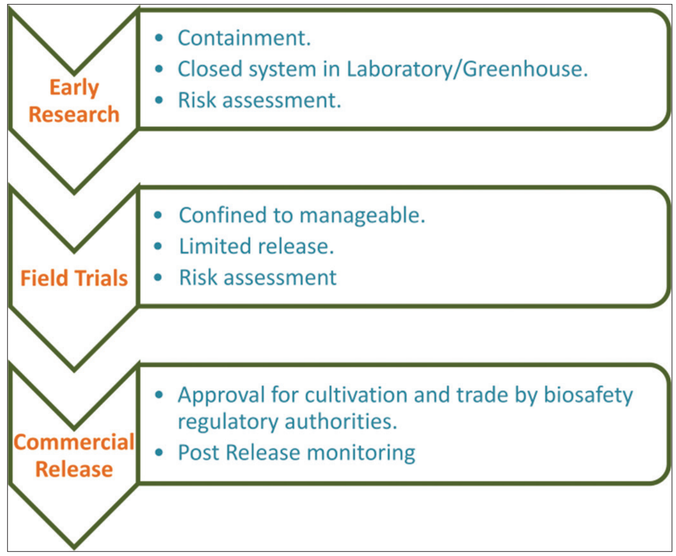

Figure 3: Workflow illustration for assessment, management, evaluation, and monitoring of potential risks.

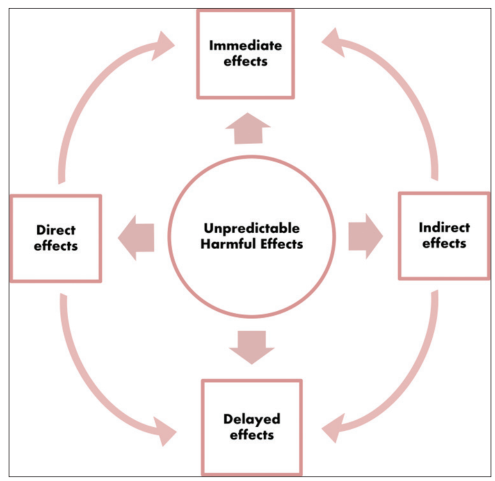

Figure 4: The unpredictable, harmful effects of GM plants. (1) Direct effects, which emerge from the genetically modified organism (GMO) directly and do not follow a causal chain of events, are primary effects on human health or the environment. (2) Indirect effects refer to consequences on human health or the environment that happen as a result of a series of connected events, for example, secondary interactions between species and their surroundings, genetic material transfer, or modifications to use or management techniques. It is likely that indirect impacts will take longer to be observed. (3) Immediate effects are those that are seen on human health or the environment immediately when a GMO is released; may be direct or indirect. (4) Delayed effects are consequences on human health or the environment that might not be noticeable during the period of the release of the GMO, but become evident either directly or indirectly, at a later time or after the release has terminated.

the risks associated. The surveillance and warning scheme with countermeasures for the detection of such unpredictable harmful effects on the environment and human health has to be included in post-releasing monitoring programs for potential effects [12-14].

The regulatory authorities have to go through the prerequisite information before approval of GM crops for trials and commercial release. The risk assessment for GM plants should involve (i) identification of potential hazards; (ii) evaluation to determine the likelihood of potential hazards; and (iii) estimation and assessment of consequences. The detailed procedures could be performed on account of defined biosafety measures, as per the regulatory authorities and organizations. The regulation on GM foods varies as (i) some countries have no regulations, (ii) some have a regulation to assess risks associated with human health, and (iii) some have a regulation to assess risks associated with health and the environment. Furthermore, the GM crops could be taken for a comprehensive evaluation and assessment with a monitoring and response plan in context with ethical and socio-economic risks [15-17] under a sustainable livelihood approach.

4. AN INDIAN PERSPECTIVE

India has the World's 4th largest crop acreage, after the USA, Brazil, and Argentina. The only GM crop approved for commercial cultivation and release in India is Bt cotton. It is estimated that the Bt cotton is cultivated in >96% of the country's cotton area, as farmers are making profits from the cultivation of Bt Cotton with increased production and export. The Indian Council of Agricultural Research (ICAR) has conducted long-term studies on the impact of Bt Cotton and found no adverse effects on soil, microflora, and animal health. The cultivation of GM crops, other than Bt Cotton, is being continuously opposed by activists and banned by the government. In 2018, the Department of Biotechnology (DBT), Ministry of Science and Technology, Government of India constituted the Field Inspection and Scientific Evaluation Committee, in the exercise of powers conferred through the Environment (Protection) Act, 1986 and Rules 1989 to examine the complaints against the unlawful cultivation of herbicide tolerant (HT) or BG-III cotton in the states of Andhra Pradesh, Telangana, Gujarat, and Maharashtra. Further, this committee has been constituted at the state level and was instructed to conduct on-the-spot inspection of Brinjal (in farms and markets) to check the spread of unapproved Bt Brinjal, in 2019. However, field trials for various other GM crops, including maize, rice, wheat, sorghum, groundnut, cotton, brinjal, and mustard, are approved. The commercial cultivation of these GM crops is yet to be approved. Consumer aversion to GM food, the high expense of regulatory compliance, and issues accessing the appropriate intellectual property rights are some of the difficulties.

India has maintained a cautious stance on GM organisms (GMOs), which has implications for its agricultural policies and global biotechnology markets. India's restrictive GMO policies limit its participation in global markets that increasingly rely on biotechnology. For instance, India's stance has affected its ability to engage with countries that support GMOs, potentially limiting access to innovative agricultural technologies that could benefit its agricultural sector [18].

India has established a complex regulatory framework for GMOs, overseen by the Genetic Engineering Appraisal Committee (GEAC). The approval process for GMOs is stringent, often resulting in lengthy delays in commercial release. For instance, the prolonged approval process for GM Bt brinjal in 2010 led to a moratorium on its commercial cultivation [19]. There is significant public opposition to GMOs in India, driven by concerns over safety, environmental impact, and the loss of traditional farming practices. A 2016 survey indicated that a majority of Indian consumers prefer organic over GM foods [20].

4.1. Biosafety and Regulations in India

Regulations in India apply to the development, import, use, research, and release of GE organisms as well as to the goods created using these organisms are governed by the rules notified by the Ministry of Environment and Forests (Ministry of Environment, Forests [MoEF]; now the MoEF and Climate Change or MoEF&CC), Government of India, on December 5, 1989, under the Environment (Protection) Act 1986 (U.S. Environmental Protection Agency). The experimental data including comparative toxicity, allergenicity, and feeding studies are required for obtaining approval from GEAC in accordance with the rules and regulations for the development, use, import, export, and storage of hazardous microorganisms, genetically engineered organisms or cells, 1989 and Revised Guidelines for Research in Transgenic Plants and Guidelines for Toxicity and Allergenicity Evaluation of Transgenic Seeds, Plants and Plant parts - 1998. These legislations and regulations, often called "Rules 1989," regulate research as well as extensive uses of GE organisms and the products derived from them across India. The DBT, Ministry of Science and Technology, and MoEF&CC are the regulatory bodies responsible for enforcing the Rules 1989 through six competent authorities as tabulated in Table 3.

To protect the interests of farmers and environmentalists, the Government of India has very strict guidelines for testing and evaluating the agronomic value of GM crops. The guidelines are drafted to address all biosafety concerns related to GM crops. Still, India has gone through several setbacks with GM technology in crops. In 2005, ICAR launched a "Network Project on Transgenic in Crops" (presently as "Network Project on Functional Genomics and Genetic Modification in Crops") to promote the innovation and development of GM Crops. Pigeon pea, chickpea, sorghum, potato, brinjal, tomato and banana are in different stages of development and case-by-case testing. In 2012, the Parliamentary Committee on Agriculture asked the Indian Government to discontinue field trials and ban GM crops. The committee stated that

Table 3: Regulatory authorities in India.

Sl. No.	Regulatory Authority	Role
1.	Recombinant DNA Advisory Committee (RDAC)	Provides advisory functions and recommendations on biosafety guidelines.
2.	Institutional Biosafety Committee (IBSC)	Approves research within an organization and ensures adherence to implementation of biosafety guidelines at organization level.
3.	Review Committee on Genetic Manipulation (RCGM)	Regulates and authorizes applications for research, field experiments, and imports.
4.	Genetic Engineering Appraisal Committee (GEAC)	Key authority that approves the large-scale use and experimental/commercial release of GMOs in the environment.
5.	State Biotechnology Coordination Committee (SBCC)	Monitors and coordinates GMO-related activities at the state level.
6.	District Level Committee (DLC)	Monitors safety regulations and installations GMO-related activities at the district level.

there are insignificant socio-economic benefits to farmers and raised issues such as ethical dimensions of transgenics and long-term impact on health and the environment. Notably, the National Institution for Transforming India Aayog released a statement in 2016, "*As a part of its strategy to bring a Second Green Revolution, India must return to permitting proven and well tested GM technologies with adequate safeguards.*" This statement supports allowing GM crops in agriculture.

On August 25, 2017, the Parliamentary Standing Committee submitted its report to Parliament on "Genetically modified crops and its impact on the environment" recommending the introduction of GM crops after critical scientific evaluation for benefits and biosafety, and restructuring of the regulatory framework for unbiased assessment of GM crops. As per the advice of GEAC, the safety assessment data for the GM mustard (Dhara Mustard Hybrid 11; DMH11) has been generated. Biosafety Research Level I (BRL I) field trial for two new transgenic indigenous Bt Brinjal varieties was conducted in three locations, Jalna, Guntur, and Varanasi, in 2009–2010. In 2020, the GEAC allowed biosafety research (BRL II) field trials of Bt Brinjal in eight states (Tamil Nadu, Karnataka, Madhya Pradesh, Chhattisgarh, Bihar, Jharkhand, Odisha, and West Bengal) during 2020–2023, only after receiving NOC from the concerned states and confirming that an isolated land area is available for this purpose. The Bt Brinjal varieties, namely, Janak and BSS-793, are indigenously developed by the ICAR. It has CryFa1-Event 142 to resist attacks of fruit and shoot borer.

4.2. India Limits Global Appeal for GMO

Political dynamics play a crucial role in GMO policy. Various political parties have adopted anti-GMO stances due to public pressure and electoral considerations. For example, the current government has faced criticism for its handling of agricultural biotechnology, impacting its approach to GMOs [21]. The adoption of GMOs is feared to disproportionately benefit large agribusinesses while marginalizing smallholder farmers. Advocacy groups argue that GMOs could lead to increased dependency on multinational corporations for seeds [22]. Environmentalists argue that GMOs pose risks to biodiversity and traditional crop varieties. India's rich agricultural diversity is considered a national asset, and there are fears that introducing GMOs could jeopardize this genetic heritage [23].

4.3. India's 2022 Policy Shift on GM Crops

In 2022, India announced significant policy changes regarding the approval and regulation of GM crops. India's 2022 policy shift towards embracing biotechnology in agriculture reflects a strategic government response to several pressing agricultural challenges. Concurrently, the persistence of unapproved GM crop adoption presents a complex challenge that must be addressed to ensure safe and sustainable agricultural practices moving forward. The Central Government aimed to bolster domestic agricultural productivity and food security through advancements in biotechnology. On March 30, 2022, a new rule was issued as an office memorandum by the MoEF&CC CS-III Biosafety Division to exempt the SDN1 and SDN2 genome-edited plants from biosafety assessment in accordance with the rule 20 of the Manufacture, Use, Import, Export, and Storage of Hazardous Microorganisms/Genetically engineered Organisms or Cells Rules 1989. These changes are followed by the recommendations from the DBT (Ministry of Science and Technology), and the Department of Agriculture, Research and Education (Ministry of Agriculture and Farmers Welfare). However, the process of developing genome-edited plants has to be carried out under containment, and regulated by Institutional Biosafety Committees under information to the Review Committee on Genetic Manipulation.

Despite the stringent regulatory framework, field data indicate that unapproved GM crops, particularly Bt cotton and other Varieties, have been adopted informally by a segment of Indian farmers. These illicit cultivations often arise from farmers' perceptions of increased yields and pest resistance associated with these crops. Reports suggest that farmers have access to unofficial seeds, and their utilization can lead to significant economic benefits, although it poses risks related to biodiversity and environmental safety [24]. In certain regions, studies have documented that farmers planting unapproved GM varieties observed improved resilience to climatic stresses, further motivating their adoption despite legal risks. These trends highlight a gap between regulatory frameworks and on-the-ground practices, as farmers prioritize immediate agricultural challenges over compliance with formal regulations [25].

The policy revamp was particularly influenced by the challenges posed by climate change and the necessity for sustainable agricultural practices [26]. The government sought to promote innovation while maintaining safety protocols, ensuring that any GM crop introduced undergoes rigorous testing to assess environmental and health impacts [27]. This shift included the introduction of a more streamlined approval process for GM crops, emphasizing the need for governmental support in deploying technologies that improve crop yields and resistance to pests and diseases. This shows India's evolving stance on GM crops and the reality of farmer behavior in the

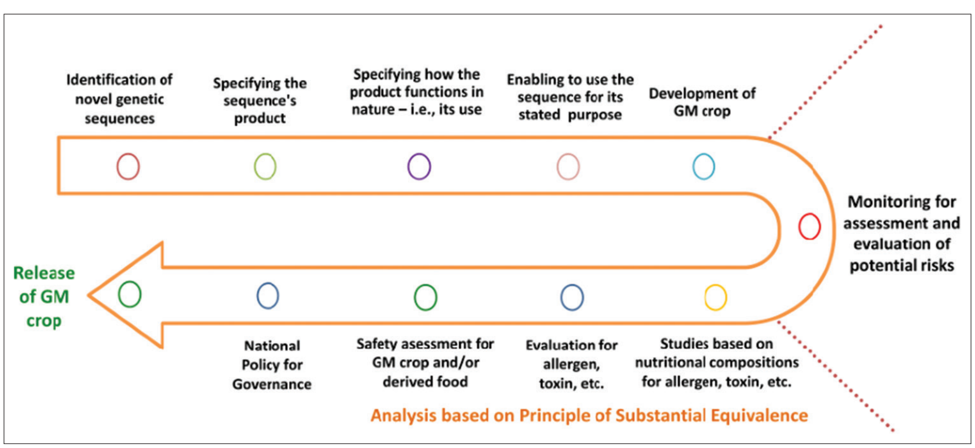

Figure 5: The illustration shows the steps involved in the development, assessment, analysis, and approval for the release of GM crops.

face of regulation. Safety assessment and Screening of GM crops and/or derived foods.

Generally, GM foods are derived from GM crops/plants. GM crop/plant variety is derived from its conventional variety, having manipulated gene(s) that leads to changes in protein(s) and associated metabolite(s) [Figure 5]. The health risks associated with GM crops are basically due to proteins expressed in GM crops from the engineered gene(s) to impart desired trait(s). These expressed proteins could be allergenic or toxic, which may be challenging for the environment along human health. A multi-factorial food safety assessment paradigm has to be utilized for every individual GM crop/food (from its first generation) and its non-GM counterpart, for substantial equivalence. In general, the safety assessment of GM crops and/or derived foods is primarily based on the concept of substantial equivalence or comparative safety assessment (CSA). The CSA is considered the first step for the safety assessment of GM crops and/or derived foods to identify similarities and differences between the foods derived from GM crops and their conventional counterpart (having a long history of safe use). The differences are subjected to further scientific analyses to identify the change in nutrients, toxins, and allergens present in GM crops and/or derived foods through wet lab experiments, bioinformatics tools, *in vitro* studies, and statistical interpretations. The strategy to access food safety was initially proposed by the WHO [28]. Then, several recommendations were published for food safety and risk associated with GM crops from several organizations like the food and agriculture organization (FAO), the World Health Organization (WHO), the Codex Alimentarius Commission (Codex), the Organization for Economic Cooperation and Development, the International Life Sciences Institute, the International Society for Biosafety Research, the European Commission (EC) and the European Food Safety Authority. The guidelines for legal and regulatory frameworks for food safety have been provided by Codex Alimentarius Commission as "Guidelines for the Conduct of Food Safety Assessment of Foods Derived from Recombinant DNA Plants (CXG 45–2003)" (CAC, 2003; https://www.fao.org/fao-who-codexalimentarius/codex-texts/guidelines/en/assessed October on 28, 2021). Due to the complexity of food constituents, food safety has to be considered a multifaceted concept. Food safety must be ensured in the light of science, keeping the risk to an absolute minimum. A science-based evaluation system

Table 4: The list of commonly used genetic elements in creating a construct with their function of utilization.

Sl. No.	Construct or its element	Purpose
1.	*CP4-EPSPS* gene (CP4-EPSPS)	Glyphosate-tolerant crops
2.	*Cry1Ab/Ac* gene (cry1Ab/Ac)	Elite synthetic fusion Bt gene in various GM Crops
3.	*Cry1A(b)* gene (cry1A[b])	Specific insecticidal activity against lepidopteran pests
4.	Cry1AC	Specific insecticidal activity
5.	Cry2Ab	Specific insecticidal activity
6.	Cauliflower Mosaic Virus 35S promoter (CaMV P-35S)	Ubiquitous promoter
7.	Figwort Mosaic Virus 35S promoter (P-FMV)	Strong constitutive promoter
8.	pRice Actin	Promoter
9.	pTA29	Promoter
10.	pUbi	Promoter
11.	pSSuAra	Promoter
12.	tg7	Promoter
13.	Nopaline synthase promoter (P-nos)	To drive the expression of selectable marker genes; regulate organ-specific expression
14.	Nopaline synthase terminator (T-nos)	Transcriptional terminator in synthetic gene constructs
15.	CaMV T-35S	*Terminator*
16.	tE9 terminator	*Terminator*
17.	tOCS	*Terminator*
18.	Phosphinothricin N-acetyltransferase gene (bar)	A selectable marker
19.	Phosphinothricin N-acetyltransferase gene (pat)	A selectable marker

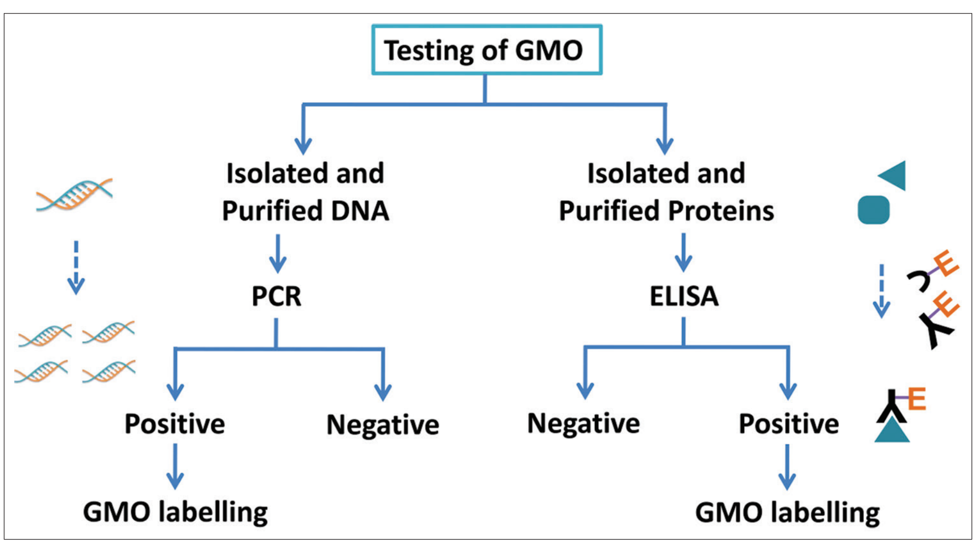

Figure 6: Schematic representation for testing of genetically modified organisms.

for screening GM crops and derived food has been supported by FAO. This may include genomics, transcriptomics, proteomics, and metabolomics studies.

The genomics and transcriptomic studies involve polymerase chain reaction (PCR), sequencing, and microarrays for detecting the differences in the sequence of the gene(s) and expression/suppression of gene(s). PCR is the most commonly used tool for analyzing genetic manipulations [Figure 6]. This involves the isolation of high-quality DNA of sufficient length (ISO/IEC 21571: 2005) to be amplified by PCR. The variants of PCR, such as multiplex PCR, qPCR (or real-time PCR), and microarray, are being employed for the detection of several targets in one experiment. The PCR and its variants are specific in detecting the inserts of DNA fragments (or the GM elements or other changes in the genetic make-up [Table 4].

Food allergies are unpleasant reactions caused by a specific protein (known as an allergen) present in food or food components. The allergen(s) may involve abnormal immunological responses mediated by the allergen-specific immunoglobulin E (IgE) antibodies as immediate hypersensitivity reactions. Some allergenic food includes milk (lactose), papaya (papain), cereals (gluten-containing wheat, barley, oats, etc.), eggs (albumin), fish (parvalbumin), peanuts (Ara h1 and Peanut lectin), soybeans (Glycinin and Soy lectin), and tree nuts (Ber e1). The proteomic studies to characterize and identify the protein(s) are carried out through enzyme-linked immunosorbent assay (ELISA), two-dimensional polyacrylamide gel electrophoresis, and bioinformatics investigations utilizing the established databases [Table 5]. The screening for newly expressed proteins encoded by the newly expressed genes in GM crops is required. Immuno-based assays, like ELISA, are a widely used analytical method to detect and quantify the isolated proteins [Figure 6]. However, the proteins may denature during food processing, and the changed conformation/structure may lead to difficulty in immunological detection.

The metabolomic studies utilize techniques such as chromatography and spectroscopy to identify, quantify, and compare the presence of metabolite(s) in GM food with its non-GMO counterpart. To elucidate nutritional, toxicological, or allergenic characteristics of constituents, the identification, potential intake, dose responsiveness, empirical biological consequences, and impact on health are usually studied on animal models. However, the assessment results may lead to conflicting interpretations due to biological and environmental variations and could be challenged subsequently.

5. IMPACTS AND IMPLICATIONS

The issues and concerns related to food safety have been around since time immemorial, starting with the trial-and-error method. Historical account for food safety was ensured to reduce food-borne illness and toxicity through different food preparation techniques, such as cooking, salting, canning, and fermentation. Recent trends in biotechnology are based on genetic engineering, which involves the modification of the genome by the transfer of genes (recombinant-DNA; rDNA) among species or by editing the genome, which may not occur naturally. The two important concerns associated with the rDNA plants, referred to as GM crop plants, are (i) the horizontal gene transfer (HGT) and (ii) the impact of a gene expressed. Recent research and literature related to GMO safety are increasing. These days, scientific research and meta-analysis are being conducted by analyzing the peer-reviewed literature on agro-environmental impact, associated risk, and biosafety of GM plants.

The term GMO has controversies as producers' and consumers' benefits are accompanied by potential risks and side-effects associated with biomedical and environmental factors. Public concerns are increasing, particularly with GM foods. Complex studies are being conducted across the globe from field to plate to evaluate the potential advantages and disadvantages of such crops and derived foods. The voice raised by various groups of scientists has failed to reach the consumers or the public - creating a negative consensus of GM among the public. The nature of GMOs and the current agricultural problems shall be comprehensively understood before making any consensus. Several intellectuals related to food, nutrition, and food safety collectively are in

Table 5: Resources available for allergenic components.

Sl. No.	Resource	Description	Weblinks
1.	AgMoBiol Allergen: Food, Pollen	The Agricultural Molecular Biology Laboratory of Peking University Protein Engg. and Plant Genetic Engg.	http://ambl.lsc.pku.edu.cn
2.	Central Science Lab Allergen: Proteins	Food and Drug Administration Centre for Food Safety and Applied Nutrition, Sand Hutton, York, UK	http://www.csl.gov.uk/
3.	FARRP Allergen: Proteins	658 allergens, The Food Allergy Research and Resource Program, University of Nebraska-Lincoln	http://www.farrp.org
4.	NCFST Allergen: Gluten	National Centre for Safety and Technology, Illinois Institute of Technology	http://www.iit.edu/~sgendel/fa.htm
5.	PROTALL Allergen: Plant	Biochemical and clinical data- The PROTALL project, FAIR- CT98-4356, The Institute of Food Research, UK	http://www.ifr.bbsrc.ac.uk/protall
6.	SDAP Allergen: Proteins	Allergenic Proteins	http://129.109.73.75/SDAP/
7.	SwissPort Allergen: Proteins	SIB Swiss Institute of Bioinformatics, Geneva)	http://us.expasy.org/cgi-bin/lists?llergen.txt
8.	WHO/International Union of Immunological Societies Allergen: Proteins	Nomenclature	http://www.allergen.org
9.	Allergome Allergen: Proteins		http://www.allergome.org
10.	Internet Symposium on Food Allergens-2002	Food Allergen data collections	http://www.food-allergens.de

agreement that GMOs are safe for human consumption [29,30]. Several incidents related to the destruction of hard work resulting by activists are being condemned by the scientific community. For example, the GM wheat and Golden Rice. GM wheat developed by CSIRO, Australia, was destroyed entirely as a protest by a non-governmental environmental organization in July 2011. In August 2013, the field of Golden Rice, managed by IRRI Philippines and other partner organizations, was attacked by activist groups. Notably, the Golden Rice is a result of 25 years of exhaustive work, designed and developed as one of the cheapest and most effective ways of delivering Vitamin A. The rice expresses high levels of β-carotene, a Vitamin A precursor.

5.1. Horizontal Gene Transfer (HGT)

DNA is chemically identical regardless of its source and is considered a harmless component of most foods that we eat. Every food that is derived from life forms contains DNA, either intact or in small fragments. Since antiquity, humans have consumed DNA from foods (whole/processed). It is estimated that about 0.1–1.0 g of DNA is being consumed daily by humans [31]. In the case of GM food, the transgenic DNA (rDNA) would be estimated to be <0.0001% of total DNA. There is no confirmation that any bacterial or plant genes are regularly incorporated into the human genome [32].

GM crops have genes conferring antibiotic resistance (AR) as selectable markers. The *AR* gene encodes for resistance to those antibiotics that are not widely used in medicine because of widespread resistance. Commonly used safe selectable markers are the *nptII* gene (confer resistance to neomycin and kanamycin) and the *aad3* gene (confer resistance to streptomycin and spectinomycin [2]. Such genes are available in the environment naturally, including gut bacteria [33].

The HGT is a frequent event in gut microbiota, facilitated by the process of conjugation and transduction in the lower GI tract [34-36]. The increased use of probiotics and other fermented food preparations has a mass of microbes that may act as donors or recipients of certain *AR* genes in the human GI tract [37]. Juricova *et al*. reported that out of 259 isolates of gut microbes, 124 contain at least one gene encoding AR in poultry [38]. Baumgartner *et al*. found that resident microbes suppress the growth and prevent the evolution of AR of individual species [39]. The possibility of *AR* gene transfer in bacteria may compromise the effectiveness of antibiotics and adversely impact the anti-microbial therapy. Bacterial gene flow is an established naturally occurring phenomenon [40]. It would be extremely improbable for a plant to transfer genes to a bacterial species because (i) the gene has to be excised precisely and intact from the plant chromosome, (ii) survive intact in the consumer's gut environment, and (iii) be acquired by the bacterium in intact form through a transformation-competent bacterium [33]. Still, the progressive development in modern biotechnology could replace or remove the utilization of *AR* genes in the future. Research on the bacterial communities in the rhizosphere provides important information on how GM crops affect the environment. According to this study, growing GM maize has little effect on the rhizosphere bacterial population and has little effect on the environment, especially on soil microorganisms [41].

The fate of recombinant DNA (transgene/cisgene) for HGT has been assessed *in vitro* in gastric, intestinal, and complete digestive tracts or body fluids in cattle, poultry, and humans. Several studies suggested the risk of HGT is insignificant in the human/animal genome. Nevertheless, the incorporation of such a transgene into the germ cells is even lower, making the inheritance of such a transgene to the following generation insignificant [42-44].

5.2. Health Concerns

The rapid digestion of the transgene or its derived proteins confirmed the absence of the transgene in GM-fed cattle and poultry in most cases. However, small pieces of DNA have been found in a few studies [45]. Agodi *et al*. reported that short pieces of the transgenes were reported in milk as possible contaminants of fecal/airborne material in feed [46]. DNA of the M13 virus, GFP, and Rubisco genes was discovered in the blood and tissue of ingested animals [47,48]. In studies on cows fed with transgenic crops such as maize and soybeans, the recombinant DNA has only been detected in the ruminal solid phase and duodenal digesta of cattle, but not in ruminal liquid and duodenal phases, milk, blood, muscle, liver, spleen, kidney, and feces [49-52].

Several studies have found contrary to such findings. In any organ or tissue sample taken from GM-fed animals, no traces of recombinant DNA or novel proteins have been discovered [53,54]. In studies on transgenic maize-fed poultry, no recombinant DNA was detected in muscle, liver, spleen, kidney, and eggs [49]. In addition, no significant differences in nutritional value and safety of feed derived from GM plants and their non-GM counterparts [55,56].

The GMO-derived proteins are degraded along with any other proteins in the gastrointestinal (GI) tract. Most dietary proteins are digested by proteases and pepsin in the GI tract, limit exposure to allergenic reactions. However, some studies have reported that the correlation between protein digestion and loss of allergenicity is limited [57,58]. Hence, comprehensive studies related to allergenicity should be carried out precisely. Food allergies are also associated with common foods such as milk, eggs, nuts, wheat, legumes, fish, crustaceans, and molluscs [59]. The presence of allergens is reported in some GM crops, like 2S albumin isoforms from Brazil nut, which were found in transgenic soybeans [53], Phosphinothricin Acetyltransferase Enzyme (PAT) protein in GM maize, and cod proteins (such as Gadc1) in transgenic potatoes [60]. The reported scientific data by researchers on the consumption of GM crops/food indicate the harmful effects on health, contradicting the studies conducted by the biotechnology-based corporate companies [61]. Abnormal young sperm has been reported in rats and mice fed transgenic potatoes and soya. The transgenic crops (such as Corn and Cotton) grazing livestock were found to have reproductive disorders or even life-threatening [62].

The safety test of GM soybeans claimed "substantially equivalent" to the conventional variety, but significant differences between the two were recorded [63,64]. Several peer-reviewed scientific reports indicate the nutritional equivalence of GMOs and their conventional counterparts. Venneria *et al*. compared the nutritional content and reported variations in the composition of fatty acid content, phenols, polyphenols, carotenoids, Vitamin C, and mineral composition in GM and conventional samples of wheat, tomato, and corn [65]. The FAO and the WHO reported that GMO foods have no allergenic effects, after being evaluated for allergenicity [66]. A meta-analysis of 21 years of field data supports the cultivation of GE maize [67].

Dunn *et al*. have reviewed 83 studies on GM crops and associated allergenicity. They reported that no human or animal was evident to show increased allergenicity of GM crops in comparison to their conventional counterparts in 80 reported studies [68]. While rest three studies have shown increased sensitization; according to the IgE-mediated mast cell reactivity. Two studies report an increase in specific IgE, eosinophil, and T-helper cell type 2 cytokines with exposure to GM corn compared with its conventional counterpart, but of no clinical significance. The study has concluded that the use of GM products and the risk of food allergies are not linked. They reported that consumption of GM proteins causes allergy in individuals who are allergic at baseline. Bt toxin Cry1Ac has been reported as a potent antigen delivered oral/nasal [69]. Even some farmworkers have IgE-mediated skin sensitization when exposed to *Bacillus thuringiensis*-based pesticides [70]. Aris and Leblanc claim the presence of Bt toxin in maternal blood [71]. Notably, the toxin is inactive in an acidic environment (as in the stomach of humans), and active in an alkaline environment (as in an insect's gut). There is no Bt toxin receptor in humans. Nelson suggests that the crystal-like proteins produced by the *B. thuringiensis* have no effects on mammals [72].

5.3. Socio-economic Concerns

There is a lot of disagreement around GM crops, which is being echoed continuously. Even, consumers have a strong perception that foods with a long history of safe use are safe for consumption. Controversies are associated with GM crops, involving farmers, consumers, government, NGOs, and environmentalists. Consumers' concerns for the quality of food were known before the advent of food derived from GM crops. GM crops may have an impact on the health of consumers that might be risky. Consumer acceptance is associated with socio-economic determinants [73], such as price premiums, option values, willingness to pay, age, gender, and educational level.

Usually, consumers consider conventional foods safe for consumption. Conventional foods have an established record of consumption for decades/centuries. The genetic manipulations and altered expression may have beneficial or detrimental effects in comparison to conventional. Therefore, evaluation and risk assessment of GMOs and GM foods should be conducted as per the Codex guidelines for allergenicity, toxicity, loss of biodiversity, gene transfer, and outcrossing (migration of genes from GM to feral and wild relatives).

The major traits gained with genetic modifications are disease and pest resistance. This makes farmers happy to cultivate their crops for more economic gain with minimal yield loss. However, the widespread release and cultivation of such GM crops at a commercial scale may pose a strong selection-for-survival pressure. This selective pressure is strong enough to be the reason behind the evolution of resistant pests, like superbugs. This may cause the failure of such GM crops in a few years, leading to controversy over the use of biotechnology, such as the Monarch Butterfly Controversy (1999) and the Seralini Affair (2012). The controversies related to safety concerns are being raised for GM crops/food on several levels by consumers, farmers, policymakers, regulatory bodies, and the government. The concern for *the modern biotechnology needed for sustainable agriculture to address the scarcity of food*, *feed*, and *fodder*; *is safe for the health and the environment?* is required to be addressed.

Developing countries like India have small and marginal farmers. Farmers cite that the high cost of weeding considerably goes down by growing HtBt cotton and using glyphosate against weeds. As claimed, cultivation of Bt Brinjal reduces the total production cost by reducing the use of pesticides. Large-scale sowing of unapproved GM crops such as HtBt Cotton and Bt Brinjal, is being reported in several states of India, such as Maharashtra and Haryana. A few farmers are arrested and charged for sowing unapproved GM variants with a jail term of 5 years and a fine of Rs 1 Lakh under the Environmental Protection Act, 1989 [74]. The right to environmental information was recently emphasized by the Indian Supreme Court in a divided decision over the release of GM mustard. One of the two judges on the court argued against the crop's release, pointing to a lack of adequate evaluation of its health effects, while the other referred to the conditional clearance as progressive. It is suggested that consumers' knowledge be used as a control variable in future studies [75]. In July 2024, the court ordered the government to engage with every relevant stakeholder, including states, independent experts, and farmers' organizations, to draft a national policy on GMOs. The action highlights how important it is for policy to be informed by both scientific data and societal demands and expectations. It demonstrates the importance of broader public involvement in synthetic biology (SynBio) interventions [76]. Small farmers' willingness to engage in collaborative GM crop farming is favorably influenced by their expectations of GM technology's profitability as well as their sense of their market adaptability [77].

The seeds are expensive in comparison to local non-GM varieties; farmers must purchase new seeds every sowing season as seeds cannot be reused. BT cotton is resistant to a specific type of cotton pest, not all pests of cotton. However, regular and prolonged spraying of herbicides/insecticides may cause the evolution of tolerant/resistant weeds/insects due to strong selective pressure in a given habitat [78,79]. Pests are developing resistance against Bt Cotton, making the GM-based strategy for pest control unsustainable [80]. To prevent this, certain crop management strategies that limit the growth of pest populations that have surmounted crop resistance mechanisms might be used. The use of GM crops with a high level of Bt gene expression and the simultaneous deployment of a refuge made up of non-GM, pest-susceptible crops constitute the most widely used resistance management technique for Bt crops, known as the high dose/refuge strategy. This strategy is based on the assumption that insects that are resistant to Bt endotoxins evolve as a result of recessive mutations that have only a low allele frequency in the population of insects. Only the extremely uncommon insects homozygous for the mutant allele will survive on the GM crops due to the high amount of Bt endotoxin expression in those crops. By planting refuge non-GM crops near the GM crop region, it should be ensured that the rare mutant homozygous resistant insects living in the GM crop area mate with non-mutant, susceptible insects from the refuge. As a result, their offspring will carry the mutant allele heterozygously and be prone to the GM crop.

It is suggested that refuges comprise 20–50% of the area that is planted with the GM crop, depending on the crop and the conditions of the area. Mathematical simulations and actual experience suggest that implementing this strategy as part of an integrated framework of pest management could prevent the emergence of resistant pests for decades [81,82]. However, the deployment of refuges may not be financially feasible or may be disregarded owing to ignorance, particularly in the case of small-scale, resource-poor farmers in developing nations [16]. Therefore, it is suggested that analyses of the emergence of resistant insect populations and compliance with refuge suggestions be incorporated into post-release monitoring programs. This might ensure that refuge suggestions are followed and that the value of GM crops that express pest resistance characteristics is maintained.

5.4. Consumer Concerns

The public debate, attitude, and expression for acceptance or rejection make several non-governmental organizations work on issues related to GMOs with explicit interests. Most research assesses people's attitudes toward GM food consumption by conducting a surveys, opinion polls, or product feedback on national and international levels [83]. The most prominent ethical concern raised with GMOs is that "*tampering with nature* may lead to unintended and unpredictable effects" [84].

An interesting case of GMO corn, StarLink (approved for animal feeding), that happened in 2000, was popularized when the corn was recalled. The StarLink corn has the gene for a Bt toxin (Cry9C), which selectively kills destructive insect larvae. The USFDA did not find any association between Cry9C and allergic reactions [85].

A study conducted in Spain concluded that the consumers demanded GM foods accompanied by strict policies; to confirm the safety of consumers, decreasing the consumer-perceived risk dealing with health-related concerns [86]. In 2011, studies related to the variables influencing consumers' decisions to choose GM-free foods were conducted in the European cities of Drama, Kavala, and Xanthi as field interviews of 337 consumers. The principal component analysis (PCA) was conducted in order to identify the factors that influence customers. To prefer GM-free products are (i) product labeling and certification – as GM-free or organic, (ii) label to claim environmental protection, a label of nutritional value, marketing issues, price, and quality. The consumers are further categorized into two: (i) influenced by elements including product cost, quality, and marketing and (ii) interested in environmental preservation and product certification [87].

Snell *et al*. conducted long-term and multigenerational studies on the effects of GM feed containing GM varieties of maize, potato, soybean, rice, or triticale on animal health. This involves 12 long-term studies for a duration of 90 days to 2 years, and 12 multigenerational studies involving 2–5 generations. They examined the parameters such as biochemical, histological, hematology, and transgenic DNA detection. They found small differences that are not statistically significant and hence have no biological or toxicological importance. The study can be concluded as GM plants could be utilized as safe food and feed because they have the same nutritional value as their non-GM counterparts [88].

6. FUTURE PERSPECTIVE

Genetic modification is a specific form of gene technology that modifies the genetic code of organisms such as plants, animals, and microorganisms. Recombinant DNA technology combines genes from different organisms, resulting in GMOs. The term GM could also be known as genetically engineered, bioengineered, or transgenic. Primarily, the GM crops grown commercially and/or field-tested are herbicide-resistant and insecticide-resistant soybeans, corn, cotton, and canola, virus-resistant sweet potato, iron and vitamins biofortified rice, banana as an edible vaccine, and a wide range of plant species that can endure harsh climates. Technologies for genetically manipulated food hold enormous promise for addressing some of the 21st century's biggest challenges. They carry some risks like any new technologies, both apparent and unforeseen. Public debates and worries over GM foods and crops fulfill the requirement on issues such as human and environmental safety, consumer choice and labeling, intellectual property rights, ethics, food security, poverty alleviation, and environmental conservation.

Apart from increasing the production of food, feed, and fodder, genetic engineering has proven potential and could be used to enhance the quality of food through bio-fortification (additional nutrition) and bio-elimination (removal of toxin and allergen), and production of metabolites (pharmaceuticals, medicines, food additives), scents, and even bioplastics. Hence, a sufficient assurance of safety to health and the environment through regulators may create a new revolution to address the scarcity. The continuous progress in genetic engineering-based plant breeding is appreciable for sustainable agriculture with minimum risks. Nowadays, the desired plants are being designed without introducing transgenes. This may change the perception of GM crops in the regulatory review process or consumer acceptance.

6.1. Biosafety

Moreover, GM crops have some changes in protein and other dependent components for the beneficial trait; which may lead to the associated risk(s) related to health and the environment. The advancement of technologies with ever-evolving science makes it easier to elucidate nutritional profiles (nutrigenomics) and toxicological profiles (toxicogenomics) without going through *in vitro* studies on animals. In addition, the global biosafety cooperation and governance have to be improved for enhanced defense capability in global biosecurity situations by (i) improving the real-time monitoring plan and early warning systems, (ii) improving the identification, prevention, and control strategies, and (iii) improving the technological management as countermeasures in emergencies.

Even though GM foods are safe, assessment and clarification of current risks and lifelong effects are required. The involvement of a panelist, including scientists, entomologists, activists, environmentalists, and others, is needed for environmental impact assessment. The cultivation of GM has to be in a confined area with a buffer zone, and the fields are far away from a biodiversity-rich region. Address scientific lacunae, precise clarity on benefits to operators, ensure labeling, and demonstrate sustainable farming with biodiversity conservation. The well-being of farmers, consumers, and the environment should be confirmed by task forces and expert committees. Current methods are constantly being improved and developed to enhance the assessment and detection of unintended consequences [89]. It is important to compare the introduced protein's structure with the structures of all known allergens. Experimental analysis of potential allergenicity has to be performed by examining the same during post-marketing monitoring of random consumers.

Food consumption is somewhat associated with culture, geography, and economy. In the future, research should use an open-ended questionnaire that allows respondents to provide extensive responses addressing all potential answers. Future studies on GM food consumption behavior should use qualitative research to capture the in-depth nuances [75]. The risk may also be associated with contamination, which is considered unavoidable. The consequences of contamination should also be taken care of before commercial approval. Food labeling regulations in the majority of nations are designed to assist people in making safe food choices when they buy and use goods [90]. Mandatory labeling of GMOs and segregation is much needed as the consumers' trust in labels for verifying the food quality and credence attributes [91]. The label should have the ingredients with potential allergens/toxins in GM food. The risk of allergies could be reduced through comprehensive evaluation for market approval testing, food safety monitoring, and adequate/appropriate labeling. For the development, production, and trade of GM foods have been established and implemented in several countries-initiatives are being/shall be taken for traceability, labeling, and authorization of GMOs in food and feed.

On the contrary, we should rely on GMOs to address the challenges associated with food and nutritional security. This could be used to make plant resistance/tolerance against biotic and abiotic stresses, reduce/remove allergens and toxins, etc. These achievements show preliminary success and may be considered to believe that the development of GMOs is the only possible solution to address agricultural loss and improve nutritional quality. As of now, no solid evidence is reported that GMOs are allergenic and/or toxic in comparison to their non-GMO counterparts.

6.2. Global Market

The use of GM crops, in particular, has led to significant sustainability breakthroughs in agriculture over the past 30 years, which have accelerated the shift from intensive tillage to almost complete elimination of tillage techniques [92]. Through increased fertilizer and water use efficiency, the use of gene-editing technology shows the potential to further contribute to improved agricultural production sustainability. Because there is less need for fertilizers when nutrient use efficiency is increased, there is less chance that nutrients will flow from cropland into nearby watersheds [93,94]. Crops that use water more efficiently can tolerate periods of lower precipitation without suffering appreciable production losses. Improvements in the efficiency of these components' utilization would significantly lessen the negative effects of agricultural production on biodiversity while also increasing yields [95]. For any advancement to have a lasting impact on our productivity, time, money, and effort are required [90].

Government initiatives for GM food, the expansion of emerging markets, and the rising need for animal feed are all responsible for the increase throughout this historic period. The market for GM crops has expanded significantly in recent years. At a cumulative annual growth rate (CAGR) of 5.8%, it will increase from $23.41 billion in 2024 to $24.77 billion in 2025. The growing populations, food waste, technological advancements, and the growing demand for biofuels are all contributing factors to the growth during the period of forecasting. Investing in gene stacking, focusing on utilizing cutting-edge CRISPR technologies, researching and developing nitrogen-fixing crops, investing in haploid induction techniques, and developing products that shorten the time needed for crop production, and focusing on forming partnerships with both established businesses and research institutions are some of the major trends for the period of forecasting. The market for GM crops is anticipated to develop significantly over the coming years. It will increase at a compound annual growth rate (CAGR) of 6.9% to reach $32.35 billion in 2029 (https://www.thebusinessresearchcompany.com/report/genetically-modified-crops-global-market-report; accessed on July 02, 2025).

Recent studies have revealed shifting consumer attitudes towards GM crops, with increased awareness regarding sustainability and health impacts. Research indicates that consumers are more likely to trust GM crops when transparency in labeling and production processes is prioritized [96]. A growing segment of the population exhibits a preference for eco-friendly agriculture, influencing their purchasing decisions; hence, marketing strategies for GM products need to highlight environmental benefits [97].

Advanced technologies such as remote sensing and soil health monitoring are being utilized to assess the environmental impact of GM crops, enhancing real-time data collection [98]. Studies indicate that GM crops can contribute to reduced pesticide use and lower carbon footprints, thus aligning with broader climate change goals [99]. Continuous environmental monitoring is vital to detect any unforeseen ecological consequences associated with GM crop cultivation and to ensure adherence to regulatory standards [100]. Integrating consumer feedback mechanisms with environmental monitoring data can enhance public confidence in GM crops and drive more sustainable agricultural practices. Collaborative efforts among stakeholders – including farmers, environmental scientists, and policymakers – are essential to develop guidelines that consider both consumer insights and ecological footprints of GM agriculture [101].

Of note in all advancements in agriculture, GM crops are a way to increase food production while reducing the negative environmental effects of conventional farming methods. This is consistent with another study that was carried out over 20 years (1999–2020) and found that using GM insect-resistant and herbicide-tolerant seed technology reduced pesticide use by 7.2% (748.6 million kg) [102,103].

6.3. Cross-country Comparisons

The cross-country comparisons for GMO crops help to understand the broader implications of GMO adoption, which involves analyzing the adoption, regulation, economic impact, and public perception of GMOs in different nations. Understanding these complex dynamics (influenced by regulatory, economic, and social factors) can inform better agricultural policies and practices, ensuring that the benefits of biotechnology are maximized while addressing public concerns. Economic benefits arising from GMO crops include increased yields, reduced pesticide use, and potentially lower production costs. A comparative study found that countries adopting GM technology, such as Argentina, experience notable economic advantages in agriculture [104]. The environmental impact of GMO crops, including biodiversity effects and sustainable practices, is a critical aspect of cross-country comparisons. Some studies indicate that GMO crops can lead to reductions in pesticide use, while others raise concerns about potential long-term ecological effects [105].

Countries have different regulatory approaches to GMOs, affecting their market access and consumer acceptance. For example, the U.S. has a more deregulated environment compared to the European Union, where stringent risk assessments and labeling requirements are in place [106]. The adoption of GMO crops varies significantly among countries. The United States and Brazil are the largest adopters, with a significant percentage of their soybean, corn, and cotton crops being GM. In contrast, many European countries exhibit lower adoption rates due to stringent regulations and public skepticism [107]. In addition, the trade policies regarding GMOs significantly affect agricultural exports. Countries that embrace GMO crops have seen an increase in exports, while those that impose bans or strict regulations face challenges in accessing international markets [108].

Public acceptance of GMO crops varies widely, influenced by cultural, social, and economic factors, and even gender. In countries such as India and China, public opinion is generally more favorable as the focus is on food security, while Western nations often exhibit more resistance due to health and environmental concerns [109]. In a cross-country survey by the Pew Research Centre, majority thinks that eating foods containing GM is unsafe. About 37% says they don't know enough about these foods to make a statement. About 70% of Russian, Polish, and Italians believe that eating GM food is unsafe. 31% of Australians believe GM foods are safe, and those who believe they are unsafe are also 31%. The percentage of people who say they do not know enough to say is typically higher in areas where GM foods are more regulated. Compared to men, women are more prone to believe that eating foods containing GM products is unsafe. Interestingly, people with higher levels of education, especially those who studied science, are more likely to believe that these foods are safe to consume in many of these populations [110].

7. CONCLUSION

Since the 1980s, crop breeding innovations have expanded by utilizing biotechnological tools. This has encouraged the development, introduction, and rapid adoption of highly successful GM crop varieties. With changing science and evolving technologies, molecular breeding and food safety risk assessment are constantly being upgraded to ensure the biosafety associated with every GM crop with greater precision. GM crop development, production, and commercialization are progressing across the world. With enhanced detection capabilities, modern food safety systems are even utilized in the detection of pathogens, allergens, and toxins. This may help us to increase consumer awareness and ease emergencies.

8. AUTHORS' CONTRIBUTIONS

The author made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work. The author is eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines. The author is presently working as an Officer in Charge for the DNA Fingerprinting Laboratory, BSSOCA, and was a Member of the Field Inspection and Scientific Evaluation Committee (FISEC) for Bihar State as directed by the Ministry of Environment, Forests and Climate Change, CS III (Biosafety) Division, Government of India.

9. FUNDING

There is no funding to report.

10. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

11. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

12. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

13. PUBLISHER'S NOTE

All claims expressed in this article are solely those of the authors and do not necessarily represent those of the publisher, the editors and the reviewers. This journal remains neutral with regard to jurisdictional claims in published institutional affiliation.

14. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

REFERENCES

1. Food and Agriculture Organization of the United Nations (FAO). High Level Expert Forum-How to Feed the World in 2050. Rome: Food and Agriculture Organization.
2. Saurabh S, Vidyarthi AS, Prasad D. RNA interference: Concept to reality in crop improvement. Planta. 2014;239:543-64. https://doi.org/10.1007/s00425-013-2019-5
3. Carpenter J, Felsot A, Goode T, Hammig M, Onstad D, Sankula S. Comparative environmental impacts of biotechnology-derived and traditional soybean, corn, and cotton crops. Council for Agricultural Science and Technology, Ames, Iowa. www.cast-science.org. Sponsored by the United Soybean Board. Available from: www.unitedsoybean.org. 2002. [Last accessed on 2024 Dec 07].
4. Lemaux PG. Genetically engineered plants and foods: A scientist's analysis of the issues (part I). Annu Rev Plant Biol. 2008;59:771-812.
5. Del-Aguila-Arcentales S, Alvarez-Risco A, Rojas-Osorio M, Meza-Perez H, Simbaqueba-Uribe J, Talavera-Aguirre R, *et al*. Analysis of genetically modified foods and consumer: 25 years of research indexed in scopus. J Agric Food Res. 2025;19:101594. https://doi.org/10.1016/j.jafr.2024.101594
6. James C. Brief 49 Global Status of Commercialized Biotech/GM Crops: 2014. Ithaca, NY: ISAAA Briefs; 2014.
7. Saurabh S. Genome editing: Revolutionizing the crop improvement. Plant Mol Biol Rep. 2021;39(4):752-72.
8. Steinwand MA, Ronald PC. Crop biotechnology and the future of food. Nat Food. 2020;1(5):273-83.
9. Butler D, Reichhardt T. Assessing the threat to biodiversity on the farm. Nature. 1999;398:654-6.
10. Jank B. Gaugitsch H. Decision making under the Cartagena protocol on biosafety. Trends Biotechnol. 2001;19(5):194-7.
11. Kinderlerer J. The Cartagena protocol on biosafety. Collect Biosaf Rev. 2008;4(S 12):16-65.
12. Bartsch D. 3. Issues and challenges in monitoring GM crop-specific traits. Genetically modified organisms In: Crop Production and their Effects on the Environment: Methodologies for Monitoring and the Way Ahead. Rome: Food and Agriculture Organization; 2006. p. 60.
13. Wilhelm R, Beißner L, Schiemann J. Concept for the realisation of a GMO-monitoring in Germany. Nachrichtenblatt Deutsch Pflanzenschutzdienstes. 2003;55:258-72.
14. Züghart W, Benzler A, Berhorn F, Sukopp U, Graef F. Determining indicators, methods and sites for monitoring potential adverse effects of genetically modified plants to the environment: The legal and conceptional framework for implementation. Euphytica. 2008;164:845-52.
15. Sonnino A, Dhlamini Z, Santucci FM, Warren P. Socio-Economic Impacts of Non-Transgenic Biotechnologies in Developing Countries: The Case of Plant Micropropagation in Africa. Rome: Food and Agriculture Organization of the United Nations (FAO); 2009.
16. Suman Sahai SS. Assessing the Socio-Economic Impact of GE Crops. Rome: FAO; 2006. p. 121-3.
17. FAO. Genetically Modified Organisms in Crop Production and their Effects on the Environment: Methodologies for Monitoring and the Way Ahead. Rome; 2005. Available from: https://www.fao.org/docrep/009/a0802e/a0802e00.htm [Last accessed on 2024 Dec 07].
18. Ghosh A. The limits of biotechnology: India's GMO policy and global impact. Biotechnol Adv. 2021;39:107-15.
19. Nandi I, Ranjan D. The GMO approval process in India: Challenges and hope. India J Agric Econ. 2018;73(1):20-35.
20. Bhan N. Consumer preferences and GMO opposition in India. J Food Policy. 2016;61:50-60.
21. Kumar S. Political dimensions of agricultural biotechnology in India. Agric Econ. 2020;51(2):231-40.
22. Sharma R. GMO and small farmers: A critical analysis. Int J Agric Food Sci. 2019;9(1):44-56.
23. Kumar V, Turner S. The role of biodiversity in India's agricultural policies. Environ Sci Policy. 2021;115:23-31.
24. Sahu P, Verma R. Unapproved GM crop adoption in India: Economic implications for farmers. Agric Econom Rev. 2023;45(2):203-18.
25. Singh A, Gupta M, Sharma K. The unregulated rise of GM crops in Indian fields: An ethnographic study. Field Stud Agric. 2023;11(4):78-90.
26. Basu S. The future of GM crops in India: A regulatory perspective.

J Agric Biotechnol. 2022;4(1):12-25.
27. Kumar R, Rai P. Navigating agricultural biotechnologies in India: Policies and practices. Indian J Agric Sci. 2022;92(3):341-52.
28. WHO. Strategies for Assessing the Safety of Foods Produced by Biotechnology: Report of a Joint FAO. Geneva, Switzerland: World Health Organization; 1991.
29. Tijerino MB, Darbishire LC, Chung MM, Esler GC, Liu AC, Savaiano DA. Genetically modified organisms can be organic. Nutr Today. 2021;56:26-32. https://doi.org/10.1097/NT.0000000000000456
30. Hefferon KL, Miller HI. Flawed scientific studies block progress and sow confusion. GM Crops Food. 2020;11(3):125-9.
31. Flachowsky G, Aulrich K, Böhme H, Halle I. Studies on feeds from genetically modified plants (GMP)-contributions to nutritional and safety assessment. Anim Feed Sci Technol. 2007;133(1-2):2-30.
32. Goldstein DA, Tinland B, Gilbertson LA, Staub JM, Bannon GA, Goodman RE, *et al*. Human safety and genetically modified plants: A review of antibiotic resistance markers and future transformation selection technologies. J Appl Microbiol. 2005;99(1):7-23.
33. Jonas DA, Elmadfa I, Engel KH, Heller KJ, Kozianowski G, König A, *et al*. Safety considerations of DNA in food. Ann Nutr Metab. 2001;45(6):235-54.
34. McInnes RS, McCallum GE, Lamberte LE, Van Schaik W. Horizontal transfer of antibiotic resistance genes in the human gut microbiome. Curr Opin Microbiol. 2020;53:35-43.
35. Van Schaik W. The human gut resistome. Philos Trans R Soc Lond B Biol Sci. 2015;370:20140087.
36. Huddleston JR. Horizontal gene transfer in the human gastrointestinal tract: Potential spread of antibiotic resistance genes. Infect Drug Resist. 2014;7:167-76.
37. Schjørring S, Krogfelt KA. Assessment of bacterial antibiotic resistance transfer in the gut. Int J Microbiol. 2011;2011:312956.
38. Juricova H, Matiasovicova J, Kubasova T, Cejkova D, Rychlik I. The distribution of antibiotic resistance genes in chicken gut microbiota commensals. Sci Rep. 2021;11:3290.
39. Baumgartner M, Bayer F, Pfrunder-Cardozo KR, Buckling A, Hall AR. Resident microbial communities inhibit growth and antibiotic-resistance evolution of *Escherichia coli* in human gut microbiome samples. PLoS Biol. 2020;18(4):e3000465.
40. Aminov RI. Horizontal gene exchange in environmental microbiota. Front Microbiol. 2011;2:158.
41. Jang YJ, Oh SD, Hong JK, Park JC, Lee SK, Chang A, *et al*. Impact of genetically modified herbicide-resistant maize on rhizosphere bacterial communities. GM Crops and Food. 2025;16(1):186-98. https://doi.org/10.1080/21645698.2025.2466915
42. Giraldo PA, Cogan NO, Spangenberg GC, Smith KF, Shinozuka H. Development and application of droplet digital PCR tools for the detection of transgenes in pastures and pasture-based products. Front Plant Sci. 2019;9:408128. https://doi.org/10.1038/s41598-017-03996-z
43. Netherwood T, Martín-Orúe SM, O'Donnell AG, Gockling S, Graham J, Mathers JC, *et al*. Assessing the survival of transgenic plant DNA in the human gastrointestinal tract. Nat Biotechnol. 2004;22(2):204-9.
44. Abbas MS. Genetically engineered (modified) crops (*Bacillus thuringiensis* crops) and the world controversy on their safety. Egypt J Biol Pest Control. 2018;28(1):1-2.
45. Nadal A, De Giacomo M, Einspanier R, Kleter G, Kok E, McFarland S, *et al*. Exposure of livestock to GM feeds: Detectability and measurement. Food Chem Toxicol. 2018;117:13-35. https://doi.org/10.1016/j.fct.2017.08.032
46. Agodi A, Barchitta M, Grillo A, Sciacca S. Detection of genetically modified DNA sequences in milk from the Italian market. Int J Hyg Environ Health. 2006;209(1):81-8. https://doi.org/10.1016/j.ijheh.2005.08.005
47. Guertler P, Paul V, Albrecht C, Meyer HH. Sensitive and highly specific quantitative real-time PCR and ELISA for recording a potential transfer of novel DNA and Cry1Ab protein from feed into bovine milk. Anal Bioanal Chem. 2009;393:1629-38.
48. Brigulla M, Wackernagel W. Molecular aspects of gene transfer and foreign DNA acquisition in prokaryotes with regard to safety issues. Appl Microbiol Biotechnol. 2010;86:1027-41.
49. Einspanier R, Klotz A, Kraft J, Aulrich K, Poser R, Schwägele F, *et al*. The fate of forage plant DNA in farm animals: A collaborative case-study investigating cattle and chicken fed recombinant plant material. Eur Food Res Technol. 2001;212:129-34. https://doi.org/10.1007/s002170000248
50. Phipps RH, Beever DE, Humphries DJ. Detection of transgenic DNA in milk from cows receiving herbicide tolerant (CP4EPSPS) soyabean meal. Livest Prod Sci. 2002;74(3):269-73. https://doi.org/10.1016/S0301-6226(02)00038-6
51. Phipps RH, Deaville ER, Maddison BC. Detection of transgenic and endogenous plant DNA in rumen fluid, duodenal digesta, milk, blood, and feces of lactating dairy cows. J Dairy Sci. 2003;86(12):4070-8. https://doi.org/10.3168/jds.S0022-0302(03)74019-3
52. De Giacomo M, Di Domenicantonio C, De Santis B, Debegnach F, Onori R, Brera C. Carry-over of DNA from genetically modified soyabean and maize to cow's milk. J Anim Feed Sci. 2016;25(2):109-15. https://doi.org/10.1016/j.bdq.2015.12.003
53. Nordlee JA, Taylor SL, Townsend JA, Thomas LA, Bush RK. Identification of a Brazil-nut allergen in transgenic soybeans. N Engl J Med. 1996;334(11):688-92.
54. Streit LG, Beach LR, Register JC, Jung R, Fehr WR. Association of the Brazil nut protein gene and Kunitz trypsin inhibitor alleles with soybean protease inhibitor activity and agronomic traits. Crop Sci. 2001;41(6):1757-60.
55. Flachowsky G, Chesson A, Aulrich K. Animal nutrition with feeds from genetically modified plants. Arch Anim Nutr. 2005;59(1):1-40.
56. Beagle JM, Apgar GA, Jones KL, Griswold KE, Radcliffe JS, Qiu X, *et al*. The digestive fate of *Escherichia coli* glutamate dehydrogenase deoxyribonucleic acid from transgenic corn in diets fed to weanling pigs. J Anim Sci. 2006;84(3):597-607.
57. Fu TJ, Abbott UR, Hatzos C. Digestibility of food allergens and nonallergenic proteins in simulated gastric fluid and simulated intestinal fluid-a comparative study. J Agric Food Chem. 2002;50(24):7154-60.
58. Herman R, Gao Y, Storer N. Acid-induced unfolding kinetics in simulated gastric digestion of proteins. Regul Toxicol Pharmacol. 2006;46(1):93-9.
59. Maryanski JH. Bioengineered Foods: Will they Cause Allergic Reactions. New York: US Food and Drug Administration (FDA), Centre for Food Safety and Applied Nutrition (CFSAN); 1997.
60. Bindslev-Jensen C, Poulsen LK. Hazards of unintentional/intentional introduction of allergens into foods. Allergy. 1997;52(12):1184-6.
61. Munro S. GM food debate. Lancet. 1999;354(9191):1727-9.
62. Maghari BM, Ardekani AM. Genetically modified foods and social concerns. Avicenna J Med Biotechnol. 2011;3(3):109-17.
63. Padgette SR, Taylor NB, Nida DL, Bailey MR, MacDonald J, Holden LR, *et al*. The composition of glyphosate-tolerant soybean seeds is equivalent to that of conventional soybeans. J Nutr. 1996;126(3):702-16.
64. Taylor NB, Fuchs RL, MacDonald J, Shariff AR, Padgette SR. Compositional analysis of glyphosate-tolerant soybeans treated with glyphosate. J Agric Food Chem. 1999;47(10):4469-73.
65. Venneria E, Fanasca S, Monastra G, Finotti E, Ambra R, Azzini E, *et al*. Assessment of the nutritional values of genetically modified wheat, corn, and tomato crops. J Agric Food Chem. 2008;56(19):9206-14. https://doi.org/10.1021/jf8010992
66. WHO. Frequently Asked Questions on Genetically Modified Foods. Geneva: World Health Organization; 2014. Available from: https://

www.who.int/foodsafety/areas_work/food/technology/frequently_asked_questions_on_gm_foods.pdf?ua=1 [Last accessed on 2021 Dec 03].

67. Pellegrino E, Bedini S, Nuti M, Ercoli L. Impact of genetically engineered maize on agronomic, environmental and toxicological traits: A meta-analysis of 21 years of field data. Sci Rep. 2018;8(1):3113. https://doi.org/10.1038/s41598-018-21284-2
68. Dunn SE, Vicini JL, Glenn KC, Fleischer DM, Greenhawt MJ. The allergenicity of genetically modified foods from genetically engineered crops: A narrative and systematic review. Ann Allergy Asthma Immunol. 2017;119(3):214-22.e3. https://doi.org/10.1016/j.anai.2017.07.010
69. Vázquez-Padrón RI, Gonzáles-Cabrera J, García-Tovar C, Neri-Bazan L, Lopéz-Revilla R, Hernández M, *et al*. Cry1Ac protoxin from *Bacillus thuringiensis* sp. kurstaki HD73 binds to surface proteins in the mouse small intestine. Biochem Biophys Res Commun. 2000;271(1):54-8.
70. Bernstein IL, Bernstein JA, Miller M, Tierzieva S, Bernstein DI, Lummus Z, *et al*. Immune responses in farm workers after exposure to *Bacillus thuringiensis* pesticides. Environ Health Perspect. 1999;107(7):575-82.
71. Aris A, Leblanc S. Maternal and fetal exposure to pesticides associated to genetically modified foods in eastern townships of Quebec, Canada. Reprod Toxicol. 2011;31(4):528-33.
72. Nelson GC. Genetically Modified Organisms in Agriculture: Economics and Politics. Netherlands: Elsevier; 2001.
73. Garcia-Yi J, Lapikanonth T, Vionita H, Vu H, Yang S, Zhong Y, *et al*. What are the socio-economic impacts of genetically modified crops worldwide? A systematic map protocol. Environ Evid. 2014;3:24. https://doi.org/10.1186/2047-2382-3-24
74. Jebaraj P. Available from: https://www.thehindu.com/news/national/sale-of-illegal-htbt-cotton-seeds-doubles/article34852355.ecen [Last accessed on 2021 Oct 29].
75. Hui X, Amponsah RK, Antwi S, Gbolonyo PK, Ameyaw MA, Bentum-Micah G, *et al*. Understanding the societal dilemma of genetically modified food consumption: A stimulus-organism-response investigation. Front Sustain Food Syst. 2024;8:1364052.
76. Todi S, Dixson H. People must be at the heart of GMO policies: Concerns over safety of genetically modified products will persist unless the public is engaged with the science behind them. Nat India. 2024. https://doi.org/10.1038/d44151-024-00149-w
77. Pang Y, Zou H, Jia C, Gu C. Expected profitability, independence, and risk assessment of small farmers in the wave of GM crop collectivization--evidence from Xinjiang and Guangdong. GM Crops and Food. 2025;16(1):97-117. https://doi.org/10.1080/21645698.2024.2445795
78. Louda SM. Insect limitation of weedy plants and its ecological implications. In: Traynor PL, Westwood JH, editors. Proceedings of a Workshop on: Ecological Effects of Pest Resistance Genes in Managed Ecosystems. Information Systems for Biotechnology. Faculty Publications in the Biological Sciences; 1999. p. 43-8. Available from: https://www.isb.vt.edu [Last accessed on 2024 Dec 07].
79. Steinbrecher RA. From green to gene revolu [Last accessed on 2024 Dec 07]. ztion: The environmentally risks of genetically engineered crops. Ecologist. 1996;26(6):273-82.
80. Zhang H, Yin W, Zhao J, Jin L, Yang Y, Wu S, *et al*. Early warning of cotton bollworm resistance associated with intensive planting of Bt cotton in China. PLoS One. 2011;6(8):e22874. https://doi.org/10.1371/journal.pone.0022874
81. Conner AJ, Glare TR, Nap JP. The release of genetically modified crops into the environment. Part II. Overview of ecological risk assessment. Plant J. 2003;33(1):19-46.
82. EPA (U.S. Environmental Protection Agency). Introduction to Biotechnology Regulation for Pesticides; 2008. Available from: https://epa.gov/pesticides/biopesticides/regtools/biotech/reg/prod.htm [Last accessed on 2024 Dec 07].
83. Hamstra A. Public Opinion About Biotechnology. A Survey of Surveys. The Hague: European Federation of Biotechnology; 1998.
84. Miles S, Frewer LJ. Investigating specific concerns about different food hazards. Food Q Prefer. 2001;12(1):47-61. https://doi.org/10.1016/S0950-3293(00)00029-X
85. Bucchini L, Goldman LR. Starlink corn: A risk analysis. Environ Health Perspect. 2002;110(1):5-13. https://doi.org/10.1289/ehp.021105
86. Martinez-Poveda A, Molla-Bauza MB, Del Campo Gomis FJ, Martinez LM. Consumer-perceived risk model for the introduction of genetically modified food in Spain. Food Policy. 2009;34(6):519-28. https://doi.org/10.1016/j.foodpol.2009.08.001
87. Tsourgiannis L, Karasavvoglou A, Florou G. Consumers' attitudes towards GM free products in a European region. The case of the prefecture of drama-kavala-xanthi in greece. Appetite. 2011;57(2):448-58.
88. Snell C, Bernheim A, Bergé JB, Kuntz M, Pascal G, Paris A, *et al*. Assessment of the health impact of GM plant diets in long-term and multigenerational animal feeding trials: A literature review. Food Chem Toxicol. 2012;50(3-4):1134-48. https://doi.org/10.1016/j.fct.2011.11.048
89. Rischer H, Oksman-Caldentey KM. Unintended effects in genetically modified crops: Revealed by metabolomics? Trends Biotechnol. 2006;24(3):102-4.
90. Goodman RE. Twenty-eight years of GM food and feed without harm: Why not accept them? GM Crops and Food. 2024;15(1):40-50. https://doi.org/10.1080/21645698.2024.2305944
91. Wu W, Zhang A, Van Klinken RD, Schrobback P, Muller JM. Consumer trust in food and the food system: A critical review. Foods. 2021;10(10):2490. https://doi.org/10.3390/foods10102490
92. Sutherland C, Gleim S, Smyth SJ. Correlating genetically modified crops, glyphosate use and increased carbon sequestration. Sustainability. 2021;13(21):11679. https://doi.org/10.3390/su132111679
93. Sathee L, Jagadhesan B, Pandesha PH, Barman D, Adavi BS, Nagar S, *et al*. Genome editing targets for improving nutrient use efficiency and nutrient stress adaptation. Front Genet. 2022;13:900897. https://doi.org/10.3389/fgene.2022.900897
94. Głowacka K, Kromdijk J, Kucera K, Xie J, Cavanagh AP, Leonelli L, *et al*. Photosystem II subunit S overexpression increases the efficiency of water use in a field-grown crop. Nat Commun. 2018;9(1):868. https://doi.org/10.1038/s41467-018-03231-x
95. Brookes G, Smyth SJ. Risk-appropriate regulations for gene-editing technologies. GM Crops Food. 2024;15(1):1-14. https://doi.org/10.1080/21645698.2023.2293510
96. Smith J, Brown L, Taylor R. Consumer trust and transparency in GM food labeling: A critical analysis. J Agric Econom. 2024;32(1):45-67.
97. Jones M, Wilson T. Eco-conscious consumerism: Trends and implications for GM crop marketing. Food Q Prefer. 2025;78:203-15.
98. Lee A, Roberts D, Singh P. The role of technology in environmental monitoring of GM crops. Environ Sci Technol. 2023;57(6):1203-10.
99. Patel S, Zheng Y. GM crops and sustainable agriculture: Assessing the carbon footprint. Sustainability. 2025;15(3):671-89.
100. Nguyen H, Thompson R, Chang E. Evaluating ecological impacts of GM agriculture: Methods and results. Ecol Application. 2024;34(2):e12345.
101. Garcia J, Kim T. Stakeholder collaboration for sustainable GM crop production: Opportunities and challenges. Agric Hum Values. 2025;42(4):671-84.
102. Brookes G. Genetically modified (GM) crop use 1996-2020: Environmental impacts associated with pesticide use change. GM Crops Food. 2022;13(1):262-89.
103. Ngongolo K, Mmbando GS. Necessities, environmental impact, and

ecological sustainability of genetically modified (GM) crops. Discov Agric. 2025;3:29. https://doi.org/10.1007/s44279-025-00180-0
104. Klümper W, Qaim M. A meta-analysis of the impacts of genetically modified crops. PLoS One. 2014;9(2):e111629.
105. Benbrook C. Who Benefits from GMOs? A Comparative Analysis of Effects from GM Crops. Geneva: Institute for Agriculture and Trade Policy; 2012.
106. EC (European Commission). EU Legislation on Genetically Modified Organisms. European: European Commission; 2021.
107. ISAAA (International Service for the Acquisition of Agri-biotech Applications). Global Status of Commercialized Biotech/GM Crops in 2020. India: ISAAA; 2021.
108. Aerni P. Global trade and biotechnology: The impact of GMOs and the role of the WTO. Food Policy. 2007;32(1):53-68.
109. Gaskell G, Allansdottir A, Allum N, Corchero C, Fischler C, Hampel J, *et al*. Europeans and biotechnology in 2005: patterns and trends. Final report on Eurobarometer. 2006;64(3):1-85.
110. Funk C, Tyson A, Kennedy B, Johnson C. Science and scientists held in high esteem across global publics. Pew Res Center. 2020;29:1-133.

How to cite this article:
Saurabh S. Genetically modified crops: Advances, biosafety, and the quest for sustainable food. J Appl Biol Biotech 2025. Article in Press. http://doi.org/10.7324/JABB.2026.244399