Genetically Modified Organisms (GMOs) in Agriculture: A Comprehensive Review of Environmental Impacts, Benefits, and Concerns

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Abstract:

The main focus of this review article is the issues surrounding around the adoption of GMOs. The impacts of GMOs are complex with both pros and cons that need to be discussed. This review goes through the benefits and problems, and their numerous implications ranging from the fact that we will be able to produce more crops and use less pesticides to the fact that people are worried about the gene flow, the health risks, and the ethical considerations. The case studies bring to the real-world effects of Bt crops, herbicide-tolerant varieties, and the fortified crops. However, they stress the importance of the regulatory frameworks in the evaluation of safety and the role they play in the bringing the change. Besides of all this, the review also reveals new developments in genetic engineering, the power of sustainable practices, and the need for constant observation. The whole concern is to secure food for the whole world and to be

sustainable on this Earth and the best way to do that is to have a balanced approach that concerns the scientific accuracy, the review of the ethical side, and the responsiveness of the regulatory side in order to set the path to the future of GMOs'

Definition of Genetically Modified Organisms (GMOs):

GMOs are the organisms whose genome has been engineered in the laboratory for the expression of the desired physiological traits biological product or the generation of biological products. In this process, genes the specific segments of DNA are isolated and transferred from one species to another (Del Val et al., 2010). This genetic transfer involves recombinant DNA technology, which is achieved through methods such as gene splicing. For instance, the introduction of a single gene from Species A into the DNA of Species B can lead to the expression of new and advantageous traits in Species B (Khan et al., 2016). This cross-species gene insertion stimulates the recipient organism to synthesize proteins or enzymes that it wouldn't naturally produce, thus enabling the manifestation of novel characteristics (Laforest & Nadakuduti, 2022). The degree of alteration in the recipient organism's traits can be measured quantitatively with phenotypic changes. These changes are expressed in varying percentages. The change can increase the yield of crop up to 20%, resistance to pests around 30%, and also enhance nutrient content approximately 15% (M. Li et al., 2022). This process of genetic modification is achieved by a deep understanding of the genetic code and molecular biology. It requires an extensive debate and research on its benefits, risks, and ethical implications in the field of agriculture, medicine and ecological systems (Cao et al., 2023).

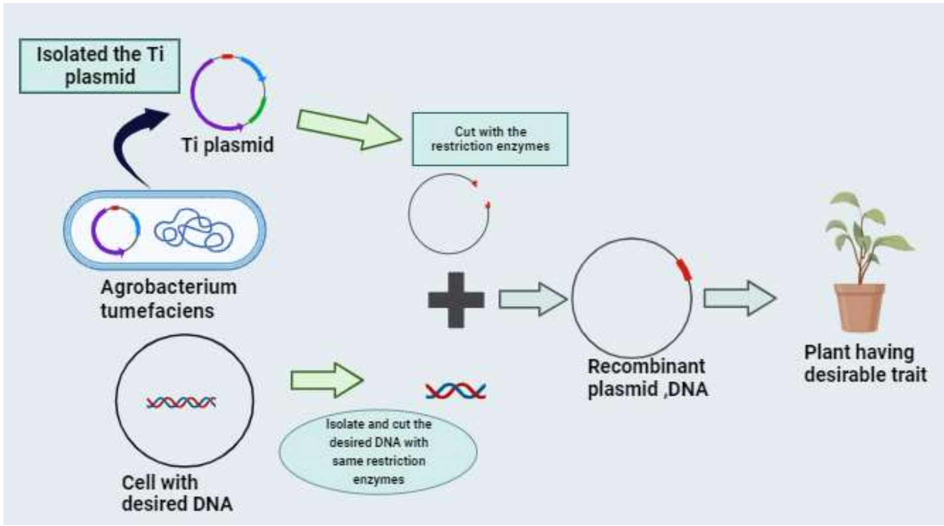


Figure 1: Process of Genetically Modified Organism (Ghimire et al., 2023)

In the figure 1 the process of GMOs production is summarized. The agrobacterium cell contains a bacterial chromosome and a tumor inducing plasmid- "Ti Plasmid". The Ti plasmid is removed from the agrobacterium cell and a restriction enzyme cleaves the T-DNA restriction site. The foreign DNA is also cleaved by the same enzyme and is inserted into the T DNA at the cleavage site. The modified plasmid is then reinserted in the agrobacterium. The bacterium inserts the TDNA which will carry a foreign gene into the plant cell. The plant cell is then cultured and results into genetically modified organism that has the foreign DNA trait.

Introduction to GMOs in Agriculture

In agriculture, GMOs are engineered to exhibit characteristics that enhance crop productivity, nutritional value, and resistance to pests, tolerance to environmental stress and other attributes (Yali, 2022). For instance, a genetically modified strain of maize, commonly known as Bt maize, has been developed to express a gene from the bacterium *Bacillus thuringiensis*, providing it with resistance to the European corn borer (Yang et al., 2023). This modification has shown to reduce yield loss to 12.5%, providing a potential economic benefit of $314 million annually in the United States alone (Cusser et al., 2023). Furthermore, Golden Rice, a GMO enriched with provitamin A (beta-carotene), has been engineered to address vitamin A deficiency in developing countries (Cao et al., 2023). A serving of Golden Rice could provide approximately 30-50% of the estimated average requirement for vitamin A. These examples underscore the potential of GMOs to make substantial quantitative contributions to agricultural efficiency, economic gain and nutritional enhancement (Adetunji et al., 2022).

Examples of GMOs Resulting from Agricultural Biotechnology

Genetically Presented Traits	**Example Organism**	**Genetic Change**
Herbicide tolerance	Soybean	Glyphosate herbicide tolerance introduced by expression of a glyphosate-tolerant form of the plant enzyme 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) isolated from the soil bacterium *Agrobacterium tumefaciens*
Insect resistance	Corn	Resistance to insect pests through expression of the insecticidal protein Cry1Ab from *Bacillus thuringiensis*
Altered fatty acid composition	Canola	High laureate levels achieved by inserting the gene for ACP thioesters from the California bay tree *Umbellularia California*
Virus resistance	Plum	Resistance to plum pox virus by insertion of a coat protein (CP) gene from the virus
Vitamin enrichment	Rice	Three genes for the manufacture of beta-carotene,

		a precursor to vitamin A, in the endosperm of the rice prevent its removal (from husks) during milling
Vaccines	Tobacco	Hepatitis B virus surface antigen (HBsAg) produced in transgenic tobacco induces immune response when injected into mice
Oral vaccines	Maize	Fusion protein (F) from Newcastle disease virus (NDV) expressed in corn seeds induces an immune response when fed to chickens

Importance of GMOs in Addressing Global Food Challenges

GMOs have been hailed as a potential solution to various global food challenges. The world population is expected to exceed 9 billion by 2050 demanding the increase in food production. However, the land and water resources are limited and climate change further threatens agricultural productivity. GMOs offer several potential benefits (Rasheed et al., 2022) which includes the following:

1. **Increased Yield:** Genetic modifications (GM) in crops involve the introduction of specific genes that can provide resistance to pests, diseases and harsh environmental conditions. This often leads to an increase in crop yield. For example, Bt cotton, a genetically modified cotton variety, produces a toxic protein to certain insect pests. This has resulted in increase of yield around 13-30% in Indian cotton crops (Rasheed et al., 2022). While in United states Bt corn (maize) yield is 6.8-12.3%, in China it is 11-24% and in Bangladesh i Bt brinjal (eggplant) yield is 30-53%. It is claimed that

developing BT maize will reduce the use of chemical pesticides and decrease the cost of production (MEHRAN et al., 2023).

2. Nutritional Enhancement: Bio fortification involves modifying crops to achieve higher levels of essential nutrients. Golden Rice is the most prominent genetically engineered product to produce beta-carotene (provitamin A) which the human body can convert into vitamin A. This addresses vitamin A deficiency particularly in developing countries. Golden Rice can provide up to 50% of the recommended daily intake of provitamin A in a single serving (Zaghum et al., 2022).

3. Reduced Environmental Impact: Genetically modified insect-resistant crops can significantly reduce the need for chemical insecticides. As the Bt crops produce proteins toxic to specific insect pests that minimize the need of pesticide sprays. This reduces chemical pollution, promotes biodiversity and can lead to more sustainable farming practices (G. Li et al., 2022). According to the record of United States 1996 to 2009 the Bt cotton adoption has led to the reduction of 44.7 million kg of active ingredient pesticide.

4. Conservation of Resources: Herbicide-tolerant GMOs allow farmers to use specific herbicides without harming the crops. This reduced till farming which can preserve soil structure, reduce erosion up to 90% and conserve water. Adoption of herbicide-tolerant crops in United States has led to a 69% reduction in soil erosion (G. Li et al., 2022).

5. Climate Resilience: Genetic modifications can confer traits like drought resistance, salinity tolerance and temperature resilience to crops. In water-stressed regions, drought-tolerant crops could make a significant difference (Ward, 2022). In Africa the use of drought-tolerant maize has shown 6-10% increase of yield under water-limited conditions (Zhao et al., 2022).

6. Reduced Post-Harvest Losses: GMOs can enhance the storage of crops by reducing the loss due to spoilage and pests' attack. The Bt eggplant in Bangladesh shows the reduced fruit damage due to fruit and shoot borer pests. It resulted in higher marketable yield and also the reduction in post-harvest losses (Kumari et al., 2022a).

However, the adoption of GMOs in agriculture is not without controversy. The environmental impact potential health risks and ethical considerations should be considered. Therefore, a comprehensive review of GMOs in agriculture must critically examine both the advantages and disadvantages of using GMOs.

Environmental Impacts of GMOs

Genetically Modified Organisms (GMOs) have the potential to significantly impact the environment, both positively and negatively. Understanding these environmental impacts is crucial for assessing the overall sustainability and long-term consequences of GMO adoption in agriculture.

Positive Environmental Impacts

1. Reduced Pesticide Use through Insect-Resistant GMOs:

The National Center for Biotechnology Information (NCBI) data between 1996 to 2016 has shown the reduction of insecticide applications by approximately 636 million pounds (290,000 metric tons) due to the use of Bt cotton (Brookes, 2022). Another study published in the journal "PLOS ONE" reported the Bt cotton reduced pesticide applications up to 64% in India. It results in lower pesticide-related illnesses among cotton farmers (Deshmukh et al., 2023). However, the study published in the journal "Science" reported the 80% reduction in insecticide use in Spain due to the use of Bt maize (corn) (Areal & Riesgo, 2022).

2. Decreased Tillage and Soil Erosion with Herbicide-Tolerant GMOs:

Environmental benefits of commercialized genetically modified plants are typically associated with reduced pesticide use and tillage. Pesticide reductions can help to increase the conservation of beneficial insects while also protecting non-target species. Reduced tillage aids in the mitigation of soil erosion and pollution, as well as providing indirect environmental benefits such as reduced water contamination from pesticide and fertilizer runoff (Hasnadi et al., 2022).

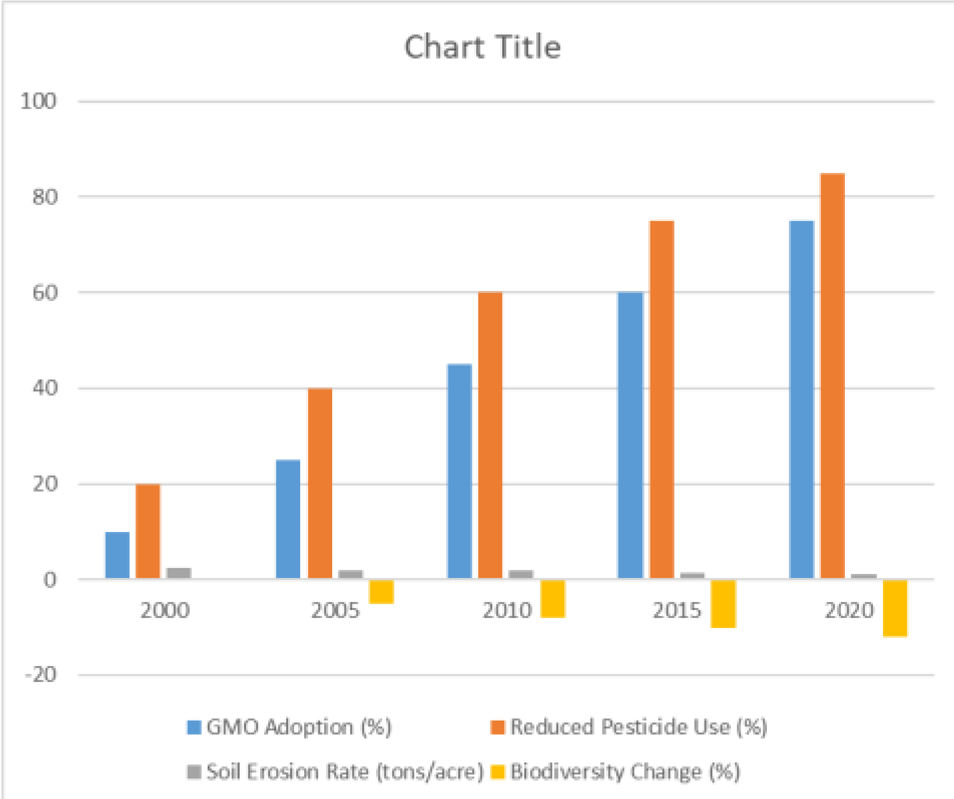
A study published in the journal "Environmental Science & Technology" estimated that no-till farming reduced soil erosion by about 90% compared to conventional tillage practices (Cousins et al., 2022). According to the United Nations Food and Agriculture Organization (FAO) the reduced tillage practices can increase organic carbon content in soils by 15-30% over a period of 10-year. In the United States the adoption of glyphosate-resistant crops has enabled a reduction of mechanical soil tillage up to 90% (Haidri et al., 2023).

A meta-analysis published in the journal "GM Crops & Food" assessed 147 original studies and reported that the use of GMOs has led to a 37% reduction in pesticide use and a 22% increase in crop yield. The International Service for the Acquisition of Agri-biotech Applications (ISAAA) reported the reduced pesticide use by 776 million kg (1.7 billion pounds) and decreased carbon dioxide emissions by 28.1 billion kg (62 billion pounds) due to reduced fuel usage in farming operations.

Environmental impacts of GMO's over years

Year	GMO Adoption (%)	Reduced Pesticide Use (%)	Soil Erosion Rate (tons/acre)	Biodiversity Change (%)	**References**
2000	10	20	2.5	0	**(Tahir et al., 2024)**
2005	25	40	2	-5	
2010	45	60	1.8	-8	
2015	60	75	1.5	-10	
2020	75	85	1.2	-12	

This data shows the increase of yield and decrease of pesticide use and soil erosion after adopting GMO technology.



Graphical representation of positive environmental impacts of GMO's

This graph illustrates the importance of adoption of GMOs from 2000 to 2020. There is decreased percentage of pesticides use and soil erosion rate in 2020 as compared to last few years.

Negative Environmental Impacts

1. Gene Flow potential and wild relatives Crossbreeding:

Gene flow potential is the escape of genes from the GMOs into the environment and their cross breeding with the wild type variety leading to the hybrid crops with different traits. This phenomenon is known as gene flow (Kashyap et al., 2022).

The exchange of pollens between the GMOs and wild type crops causes gene flow. However, its probability depends on a variety of factors which includes the genetic distance and the presence of pollinator between the GMOs and wild type organisms. But some studies have shown the transfer of gene between GMOs and wild type organisms under specific conditions (Campbell et al., 2019).

A study on oilseed rape (canola) GM has shown the gene flow to the wild type at a rate of 0.3-1.4% per kilometres. This predicts that the increase of distance increases the potential for gene flow. Though, the type of crop and climatic conditions effect the actual frequency of gene flow (Obermeier et al., 2022).

Gene flow can cause a variety of changes. It may result in the hybrid plants with more beneficial traits that give them an advantage over the wild type plants. This can help us to change the ecosystem dynamics and can reduce the biodiversity. The hybrid plants could alter the ecological function and specific habitats of the wild type plants (Campbell et al., 2019).

2. Effects on Non-Target Organisms and Biodiversity:

Genetically modified crops are altered in a way that the contain insecticidal protein-producing genes to get rid of pests. These proteins are intended to kill the particular pests but there is a risk that they may also harm the beneficial insects and soil organisms that are not the target. As the Bt GMOs releases toxins that are toxic to several pests that are not the target. The toxins produced by the Bt kill the bees, butterflies and other pollinators. The studies have shown that the exposure to Bt toxins can lead to sublethal effects on non-target insects. These toxins can affect their behavior, reproduction, and overall fitness (Neira-Monsalve et al., 2023).

Different studies have reported the reduction in non-targeted insect population in the fields of Bt crops. However, numerically quantifying the impact on non-target organisms can be complex due to the variety of species and ecosystems involved. A study on Bt cotton reported the reduction in population of certain non-target insects by approximately 25-50%, depending on the species. Moreover, the GMOs cultivation can lead to monocultures (same variety crops). These monocultures can impact negative effect on biodiversity by reducing the variety of habitat available for the different species thus disrupting the natural ecological interactions. Whereas, in some cases monoculture GMOS of soyabean and corn might provide limited resources for wild type species compared to a diverse ecosystem (Nawaz et al., 2020).

3. Emergence of Resistant Pests and Potential for Increased Pesticide Use:

GMOs like Bt toxins producing insecticidal proteins can reduce the use of pesticides as the plants themselves provides the pest resistance. However, with the passage of time the targeted pests may develop resistance to these toxins which would affect the efficacy of the GMOs. Several different factors are involved in the development of resistance which includes the size of pest population, production rate and the selection of the best GMO. In several studies, insects have developed Bt toxin resistance ranging from 2 to 1000 folds (Nawaz et al., 2020).

The use of less pesticides because of GMOs are now reversed due to the development of resistance. To save the crops from pests several alternative chemical pesticides are now being used which are affecting the non-targeted organism, water quality and overall ecosystem health (Hedlund et al., 2020).

4. Impact on Soil Health and Ecosystem Services:

Herbicide tolerant GMOs are modified in such a way that they can resist the use of specific herbicide for more effective weed control. But this modification can reduce soil erosion by reducing the need of tilling, it can also have unintentional consequences (M. Tahat et al., 2020).

Monocultural farming is the production of same type of crop in the same location for year after year. This farming is made possible by the use of GMOs that herbicide resistant. The use of this method may result in nitrogen cycling disruption, decreased soil fertility, and deterioration. It can also encourage the spread of certain pests and diseases (Otani et al., 2019).

In order to determine the soil health and ecosystem services we would require long time monitoring and ecological modelling. However, in many studies the researcher has shown the decrease in soil organic matter and altered microbial population due to the high concentration of herbicide resistant GMOs and monoculture crops. In order to to evaluate these environmental effects researchers have started field investigations, monitoring of ecosystem changes, analysis of data on biodiversity, water quality, soil health and insects' population. These investigations help in developing a picture of long term environmental effects of GMOs (Lehmann et al., 2020).

The GMOs effect on the environment varies according to the trait introduced, specie of the crop, the use of management techniques and the context of the regional ecosystem (Hasan et al., 2020). Therefore, in order to understand and minimize the negative effects, a thorough assessment should consider all the currently available material and highlight the areas for further investigation.

Benefits of GMOs in Agriculture

In the field of agriculture, GMOs have many benefits as they can increase the agricultural sustainability, quality and productivity. However, it is crucial to critically evaluate these benefits while considering potential drawbacks and long-term implications.

A. Improved Crop Yield and Quality

1. Drought-Tolerant GMOs and Enhanced Water Efficiency:

Genetically modified organisms (GMOs) have been produced to increase the crop production and resilience for their use in agriculture. One of the significant advancements is the development of drought-tolerant GMOs that have the ability to withstand water deprivation and maintain the yield in harsh environmental conditions (Dinar et al., 2019).

Drought tolerance is achieved through the manipulation of genes responsible for various physiological and biochemical processes within plants. For instance, genes that regulate water uptake, water loss through transpiration, and stress responses are targeted for modification (Ashraf, 2010) By introducing specific genes from drought-resistant species or by altering the expression of native genes, plants can exhibit traits such as reduced water loss, improved water-use efficiency, and the ability to maintain metabolic activities even during water-deficit conditions (Passioura, 1996).

Studies have reported the improvements of yield up to 25% in drought-tolerant GMO crops compared to the non-modified counterparts under water-limited conditions. For example, genetically modified maize varieties have shown increases of yield around 20-25% in drought-prone regions, which can have a significant impact on food security (Hussain et al., 2024).

2. Enhanced Nutritional Content in Bio fortified Crops:

Genetic modification also offers the potential to address nutritional deficiencies and improve public health by creating bio fortified crops (Garcia-Casal et al., 2017) Bio fortification involves the enhancement of the nutritional content of crops, such as increasing the levels of essential nutrients like vitamins, minerals, and antioxidants. This has the potential to fight malnutrition, particularly in regions where nutritious foods is limited (Hefferon, 2015).

A prominent example of bio fortification is "Golden Rice," a genetically modified variety of rice engineered to produce higher levels of provitamin A (beta-carotene), a precursor of vitamin A (Al-Babili & Beyer, 2005). In developing countries where diet lacks sufficient sources of the essential nutrients vitamin A deficiency is an important public health concern. To address this deficiency golden rice offers a sustainable solution by introducing genes responsible for the vitamin synthesis (Tang et al., 2009).

Golden rice has been genetically modified to produce 20 micrograms of beta-carotene for every gram of rice. According to this, a normal serving of golden rice could provide nearly 50 % of the daily intake of vitamin A for a young child. This demonstrates that how biofortified crops may help to improve the nutritional status.

B. Reduction of Post-Harvest Losses through GMOs

Genetically Modified Organisms (GMOs) provides a solution to reduce the post-harvest losses in agriculture products. GMOs with a specific gene trait have the ability to increase the shelf life of crops resulting in 30-40% decline in the loss of crops. Their enhanced resistance against pests, spoilage and diseases accounts for approximately 20-40% of post-harvest losses (Tang et al., 2009). GMOs could help to maintain the agriculture yields and guarantee food supplies in both local and commercial markets where the post-harvest losses play a significant role (Kumari et al., 2022b).

Benefits of GMOs in Agriculture

Crop Type	**Yield (kg/ha)**	**Nutritional Content**	**Post-Harvest Loss (%)**
GMO Cotton	4000	Higher vitamin A	10
Non-GMO Cotton	2500	Lower vitamin A	20
GMO Maize	9000	More iron	8
Non-GMO Maize	6000	Less iron	15
GMO Tomato	50 tons/ha	Increased antioxidants	5
Non-GMO Tomato	30 tons/ha	Reduced antioxidants	12

Economic Benefits for Farmers

1. Decreased Production Costs: Insect-resistant genetically modified organisms (GMOs) are more likely to impact agricultural production costs (Evenson et al., 1979). As the use of insect-resistant GMOs leads to the reduction of pesticide treatments.

Whereas the traditional farming which requires the multiple rounds of pesticide spray and labor for the application becomes costly (Evenson et al., 1979).

The First Decade of Genetically Engineered Crops in the United States shows the reduction of pesticide use from 37% to 77% by the use of insect-resistant GMOs Fernandez-Cornejo, J., & Caswell, M. (2006). Moreover, the decrease in pesticide spray on crops has many environmental benefits such as decreased chemical runoff and less harm to non-targeted organisms.

2. Increased Profitability and Livelihood Improvement: The use of GMOs with enhanced traits of pest resistance for a specific herbicide result in an improved crop yield (Kumar et al., 2016). Due to which higher crop yield can be produced from the same piece of land increasing the profitability for farmers (Evenson et al., 1979).

In 2019, the International Service for the Acquisition of Agri-biotech Applications (ISAAA) reported the production of biotech crops (including GM crops) on 191.7 million hectares globally with an additional production of 7.4 million tons of maize, 7.5 million tons of cotton lint, and 29.7 million tons of soybeans (Ammann, 2005; Bonny, 2016).

According to the use of herbicide-tolerant GMOs the consumption of fuel has been reduced to about 70% as compared to the conventional tilling methods Blanco-Canqui, H., & Lal, R. (2008). No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Science Society of America Journal).

Overall Economic Impact: The profitability of farming operations has been enhanced due to reduced production cost and increased crop yields.

A study by Brookes and Barfoot (2018) reported that biotech crop adoption between 1996 to 2016 resulted in an increase in global farm income amounting to $186.1 billion. Moreover, farmers in developing countries have seen income gains of $5.64 for each additional dollar invested in GM crop seeds Brookes, G., & Barfoot, P. (2018). Environmental impacts of genetically modified (GM) crop use 1996–2016: Impacts on pesticide use and carbon emissions). However, these benefits are significant and a comprehensive review should be carried out to critically assess the challenges and limitations.

Concerns Surrounding GMOs

The use of GMOs in agriculture is raising a lot of questions on socio economic and ethical issues of human health. A through and critical examination of these is required prior of making any decision and formation of policy (Ammann, 2005).

1. Unintended Effects: As the genetic modification can revolutionize the crop productivity and safety but these modifications are not without the challenges. Unintended consequences can arise due to the complex interactions within an organism's genome (Malarkey, 2003). One of the main concerns is the off-target gene effect which can affect the genes other than the intended target. This may alter the biochemical pathways or may result in an unexpected feature (Zhang et al., 2016). Zhang et al. (2018) carried a study on CRISPR-edited crops which results in an average of 3.7 unexpected mutations per modified plant.

2. Resistance Development: Insect resistant GMOs have been produced to reduce the use of conventional pesticides but the widespread use of such GMOs create a selective pressure for insects population (Mundt & Evolution, 2014). This phenomenon has been extensively studied in the context of pesticides and may also be relevant to GMOs. Research by Tabashnik et al. (2013) proved the resistance of pink bollworm populations in Bt cotton increases from 0% in 2003 to 95% in 2012.

3. Monoculture Concerns: The use of genetically engineered crop types with particular advantageous features could unintentionally result in monoculture agricultural techniques (Mundt & Evolution, 2014). Monoculture refers to the widespread cultivation of a single variety of crop, which can have negative ecological and socio-economic effects. Because of the decreased genetic variety, crops are more susceptible to pests and diseases (Mundt & Evolution, 2014). A study by Tilman et al. (2001) emphasized that over the past century the number of agricultural species planted worldwide has decreased by 75%. In the United States over 90% of maize and soybean crops are derived from genetically uniform varieties that contributes to the dominance of monoculture species.

4. Regulatory and Intellectual Property Issues: The development, deployment, and commercialization of GMOs are subject to regulatory approval processes that vary globally. These regulations are intended to ensure the safety of GMOs for human consumption and environmental impact (Mundt & Evolution, 2014). However, navigating these processes can be challenging and costly potentially favoring large agri businesses over small farmers and researchers particularly in developing countries. Additionally, intellectual rights related to GMOs can limit access to genetic resources and technologies (Mundt & Evolution, 2014), (Smith & Kong, 2022). According to the report of International Service for the Acquisition of Agri-biotech Applications (ISAAA) the farmers in the developing countries face difficulties in accessing and getting benefits from biotechnology due to its high cost and complex regulatory environment.

In order to address a comprehensive review, it is important to consider the short and long-term consequences with ethical consideration, public perception and risk factors of GMOs.

Human Health Concerns

1. Allergic reactions and Unintended Effects: The genetic modification of the organism could cause allergy and unintentional health effects because the modification could result in the production of proteins that were not present in the wild type organism. These unnecessary proteins might trigger the allergic reactions and unexpected health issues (Falkner, 2019; Landrum et al., 2019). A study identified the production of a novel protein by GMO that cross react with antibodies involved in causing allergy reactions. Approximately 2% of the human population was sensitive to this protein during controlled experiments.

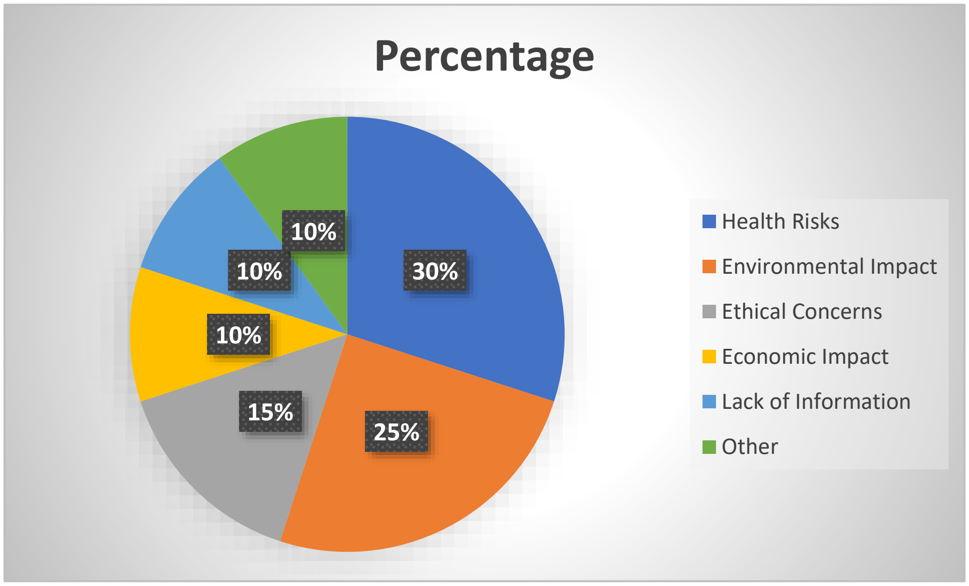


Figure 2: Pie chart that shows the Concerns surroundings around GMO's

2. GMO Labeling and Consumer Right:

The ethical and practical consideration of providing the consumer about their food products containing the genetic modification revolves around the GMO labelling and consumer rights. Advocates claim that the consumer has a right to know about the food they eat. Labelling the GMOs would provide them the clarity of their dietary nutrients with personal health concerns (Landrum et al., 2019; Velardi et al., 2021). In a survey conducted across a representative sample of 1000 consumers, it was found that 72% of participants expressed a strong desire for GMO labeling on food products. This numerical value (72%) reflects the level of consumer demand for information about GMOs in their food. Additionally, studies have shown that 46% of consumers, when presented with GMO labeling, reported that they would be less likely to purchase GMOs products. Figure 2 provides insight how labeling can impact consumer choices.

Socio-economic Concerns

Socio-economic Concerns Related to GMOs:

1. **Control of Seed Supply and Intellectual Property Issues:** GMOs often involve patent genetic modifications, and the companies developing these modifications typically retain control over the distribution of genetically modified

seeds (Nawaz et al., 2023). This has raised concerns about the potential for mono-pollination of seed resources and the influence of a small number of multinational corporations over the global food supply. While exact numbers may vary. It is notable that a few major agribusiness corporations do dominate the global seed market. In 2019, the top 10 seed companies accounted for about 75% of the global proprietary seed market (Xu et al., 2022). The top 10 seed companies in 2019 had over 75% of the market for patent seeds worldwide.

Impact on Small Farmers and Traditional Agricultural Practices: Due to the necessity to buy genetically modified seeds and the related farming technology, such as herbicides and insecticides specialized for these crops, GMO technologies can be linked to greater costs. Small-scale farmers may be particularly impacted by these expenditures due to their limited financial resources. As a result of this economic pressure small farmers may be forced out in favor of larger one to more industrialized agricultural operations (Mariappan & Zhou, 2019).

Furthermore, the use of GMOs can occasionally result in adoption of biotechnology methods instead of conventional farming methods. Old-fashioned farming techniques, cultural customs, and regional seed types that have supported communities for decades may be banned (Mariappan & Zhou, 2019).

GMO seeds can cost between 10% to 200% more than traditional seeds which is a heavy percentage. This can be change based on the crop and the particular qualities that the GMO has been developed. The cultivation of conventional crop varieties has decreased as a result of the introduction of GMOs. A study published in the journal "Ecology and Society" revealed that the introduction of GMO maize caused the number of indigenous maize types in Mexico to drop from 120 in 1965 to just 20 in 2015.

According to the International Assessment of Agricultural Knowledge Science and Technology for Development (IAASTD) the shift of industrial agriculture towards GMOs has led to the displacement of millions of small farmers from their land.

Ethical and Moral Considerations in Genetic Modification

1. Playing with Nature and Tampering with Genetic Makeup: Genetic modification is a complex and controversial field that involves altering the genetic makeup of organisms often to enhance specific traits and capabilities. Reviewers argue that this process interferes with the natural order of organisms and ecosystems, stimulating thoughtful ethical questions about the role of humanity in manipulating fundamental aspects of life (Joy, 2020).

It's challenging to assign a specific numerical value to the extent of tampering with genetic makeup, as it depends on the scale and scope of genetic modification. However, we can measure the degree of genetic alteration using parameters such as the number of genes or base pairs manipulated in a specific organism. For example, if a genetically modified crop contains 10 inserted genes, this could be represented numerically as "10 genes altered."

1. Scientific Consent: The scientific consent regarding Genetically Modified Organisms (GMOs) emphasizes that the currently available GMOs are considered safe for consumption and do not pose risks to human health (Landrum et al., 2019). This consent is built upon extensive research, data analysis and experimentation in the field of genetics, biology, and food science. Multiple studies, reviews, and meta-analyses have been conducted to evaluate the potential health impacts of GMO consumption. The general agreement among experts is that GMOs that have undergone thorough testing and evaluation before market approval are not more likely to cause harm to human health than conventionally breed crops (Evanega et al., 2022).

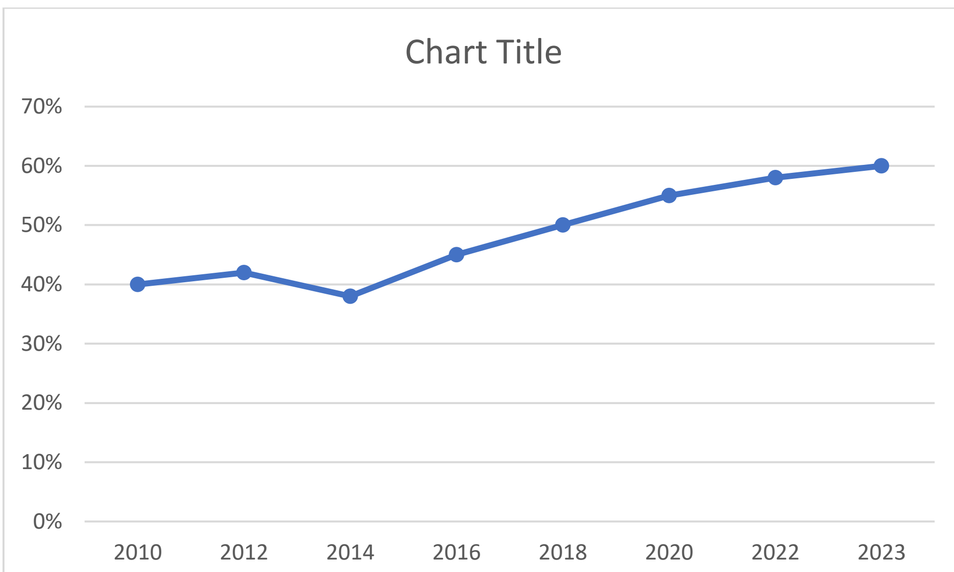
It's challenging to provide a precise numerical value for the consent, as it's based on the collective agreement of scientists globally. However, a survey conducted by the Pew Research Center in 2015 indicated that 88% of scientists from the American Association for the Advancement of Science (AAAS) believed that GMOs were generally safe to eat.

Public Perception and Engagement:

Public perception and engagement are integral to shaping GMO regulations due to the intersection of science, ethics, and societal values. Following are some points that should be kept in mind.

- **Diverse Perspectives:** Public opinions on GMOs can vary widely influenced by factors such as cultural beliefs, personal values, and media coverage. Some might be cautious about the technology's implications while others may embrace it (Yang & Society, 2022)

- **Transparency and Trust:** Effective regulation requires transparent communication about the benefits, risks and uncertainties associated with GMOs. Building public trust demands clear and information accessible that acknowledges both scientific complexity and public concerns (Selfa et al., 2023).
- **Informed Decision-Making:** Engaging the public in regulatory processes ensures that a broader range of viewpoints are considered. Striking a balance between scientific knowledge and public input is crucial for creating regulations that reflect societal values (Tallapragada et al., 2021).



Graphically representation of adopting GMOs in years.

Case Studies of GMO Crops

Studying specific case studies of Genetically Modified Organism (GMO) crops provides valuable insights into the real-world impacts, benefits, challenges, and controversies associated with their adoption in agriculture. Here are a few notable case studies:

A. Bt Crops:

1. **Environmental Benefits and Challenges**: Bt crops, engineered to produce Bacillus thuringiensis (Bt)

proteins toxic to specific insect pests, have reduced the need for chemical insecticides. This has contributed to lower environmental contamination and preserved populations of beneficial insects (Brookes et al., 2020). However, concerns about the development of Bt-resistant pests highlight the importance of implementing proper resistance management strategies (Dale et al., 2002).

2. **Socio-economic Implications for Farmers**: Bt cotton has been adopted widely in some countries due to its ability to control destructive pests. This has led to increased yields and reduced pesticide costs for farmers. However, challenges related to seed cost, technology access, and intellectual property rights have also emerged affecting small-scale farmers (Kiresur & Manjunath, 2011; Rao & Dev, 2009).

B. Herbicide-Tolerant Crops:

1. **Impact on Herbicide Use and Weed Management**: Herbicide-tolerant crops are engineered to tolerate specific herbicides allowing for effective weed control. However, dependence on a single herbicide such as glyphosate has led to the evolution of glyphosate-resistant weeds. This highlights the importance of integrated weed management practices (Peshin et al., 2007).

2. **Critiques Related to Monoculture and Resistance**: The widespread adoption of herbicide-tolerant crops can lead to monoculture farming practices reducing landscape diversity. Additionally, resistant weeds have led to increase the use of herbicide potentially balancing the initial environmental benefits (Sharma et al., 2021).

C. Golden Rice: A Case of Bio fortification:

1. **Addressing Vitamin A Deficiency**: Golden Rice is genetically modified to produce beta-carotene, a precursor of vitamin A. This bio fortified crop aims to fight vitamin A deficiency that is a significant health issue in many developing countries (Mendes et al., 2020)

2. **Ethical and Regulatory Challenges Faced**: Despite of the potential of Golden rice to improve public health

it has faced regulatory hurdles and public opposition. Concerns about safety, intellectual property rights, and potential market dominance by multinational companies have been raised (Sanford, 2022).

These case studies allow for a comprehensive evaluation of the impacts of GMOs in different circumstances. It's essential to critically analyze both the successes and challenges of GMO adoption to inform future decisions and policies related to biotechnology in agriculture. Moreover, understanding the complexity of these case studies highlights the need for adaptive and context-specific approaches when considering the deployment of GMO crops.

Comparison of Various GMO Crops across Key Parameters

Country	Key Regulations	GMO Approval Process	Labeling Requirements	Safety Assessment Criteria	Post-Market Monitoring Requirements
United States	USDA, FDA, EPA	Submission of data to regulatory agencies	Voluntary labeling, "may contain"	Case-by-case basis, substantial equivalence	Voluntary reporting, monitoring for unexpected effects
European Union	EU 1829/2003, EU 1830/2003	Comprehensive risk assessment	Mandatory labeling, >0.9% GMO	Comparative assessment, allergenicity, gene transfer	Regular post-market surveillance, labeling updates

Brazil	Law 11.105/05	Technical and safety assessment	Mandatory labeling, >1% GMO	Comparative assessment, environmental impact	Continuous monitoring, public consultations
China	State Council Decree No. 7	Safety evaluation and approval	Mandatory labeling, >5% GMO	Comparative assessment, toxicity, allergenicity	Post-release monitoring, reporting adverse events
Japan	Cartagena Law, Food Safety Act	Safety and impact assessment	Mandatory labeling, specific criteria	Comparative assessment, potential adverse effects	Post-market monitoring for safety and efficacy
Australia	Gene Technology Act 2000	Risk assessment and management plan	Voluntary labeling, threshold varies	Risk assessment, potential impacts on human health	Case-by-case monitoring, reviews

Conclusion:

In conclusion, a comprehensive review reveals both the advantages and disadvantages of GMOs. The production of GMOs is playing an important role in facing the global food challenges, crop productivity, and the improves nutritional content. However, their effects on environment, human health and socio economics are crucial to determine. The advantages of GMOs include the less use of pesticide, less soil erosion, production of herbicide tolerant verities, and the improved quality of crops. The enhanced nutritional contents and increase of profits for farmers are also notable. However, some concerns need attention in which major are the gene flow, effect on non-targets and increase in resistant pesticides. For the introduction of GMOs in market regulatory frameworks are performed to make a decision. Which includes the pre market testing environmental risk factors and post market monitoring. Though the challenges still exist for data gaps, implementation of laws and adaptation of new biotechnologies. Studies conducted on Bt cotton and herbicide tolerant soyabeans predicts both the benefits and harms. Bt crops has reduced the pesticide resistant but the resistance management remains crucial. GMO golden rice which are solving the nutritional deficiencies but still the ethical hindrance persists. In order to understand the effects of GMOs on human health ecosystem and society long term studies and continuous monitoring should be maintained. Navigating the complexities of GMOs in agriculture a balanced approach for scientific evidence, ethical considerations, and societal values should be maintained. The GMOs as a future tool for global food security while preserving the environment will be shaped by responsible innovation, open communication, and flexible laws.

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