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The Use of Genetically Modified Maize in Sustainable Agriculture

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Abstract Genetically modified (GM) corn has a significant impact in modern agriculture and plays a crucial role in sustainable agricultural practices. Related case studies have shown that genetically modified corn can increase crop yield by an average of 22%, reduce the use of chemical pesticides by 37%, and have also been proven to increase farmers' profits by 68%. In regions such as Spain and Portugal, genetically modified corn reduces the environmental impact of herbicide and insecticide use by 21%. In addition, genetically modified corn has shown resistance under drought conditions, especially in some temperate regions, thereby stabilizing yield under different rainfall gradients. This technology also promotes better weed management and reduces the adverse effects of maize continuous cropping. Incorporating genetically modified corn into sustainable agricultural practices brings enormous benefits, which contribute to environmental sustainability and food security. However, the widespread adoption of genetically modified corn still faces challenges. Solving these issues through scientific research and effective communication is crucial for maximizing the potential of genetically modified corn in sustainable agriculture. This study emphasizes the importance of integrating genetically modified corn into sustainable agricultural practices and provides insights for future progress, aiming to enhance the role of genetically modified corn in promoting sustainable agriculture.
Keywords Genetically modified maize; Sustainable agriculture; Agricultural benefits; Economic impact; Environmental impact

1 Introduction

Genetically modified (GM) maize has been a significant advancement in agricultural biotechnology since its first commercialization in 1996. The adoption of GM maize has been rapid, particularly in the United States, where by 2012, 88% of maize was planted with GM hybrids (Chavas et al., 2014). These modifications typically involve the incorporation of traits such as herbicide tolerance, insect resistance, and improved nutritional quality, which have collectively contributed to increased maize yields and reduced agricultural risks (Yassitepe et al., 2021). The development of GM maize has also been facilitated by advances in plant transformation technologies, which have significantly improved the efficiency and effectiveness of genetic modifications (Yassitepe et al., 2021).

Sustainable agriculture aims to meet the needs of the present without compromising the ability of future generations to meet their own needs. It involves practices that are environmentally sound, economically viable, and socially responsible. The use of GM maize plays a crucial role in sustainable agriculture by enhancing crop yields, reducing the need for chemical inputs such as insecticides and herbicides, and minimizing the environmental impact of farming practices (Brookes, 2019). For instance, the adoption of GM insect-resistant maize in Spain and Portugal has led to a significant reduction in insecticide use and associated environmental impacts, while also increasing farmers' incomes (Brookes, 2019).

This study aims to systematically evaluate the role of genetically modified maize in promoting sustainable agriculture. This includes assessing the agronomic, economic, and environmental impacts of GM maize cultivation. Specifically, this study analyzes the yield performance and risk mitigation associated with GM maize compared to conventional varieties; evaluates the environmental benefits of reduced chemical inputs and their implications for ecological sustainability; investigates the socio-economic benefits for farmers, including income gains and resource savings and addresses the potential health and environmental risks associated with GM maize and propose strategies for mitigating these risks. By comprehensively examining these aspects, the study seeks to provide a balanced perspective on the use of GM maize in sustainable agriculture and offer insights for future research and policy development.

2 Historical Context and Adoption of GM Maize

2.1 Early development and commercialization of GM maize

The development of genetically modified (GM) maize began in the early 1980s with the advent of plant transformation techniques. The first commercial GM crops were introduced in the mid-1990s, marking a significant milestone in agricultural biotechnology. By 1996, GM maize was commercially available, and its adoption quickly accelerated due to its enhanced traits such as insect resistance and herbicide tolerance (Chavas et al., 2014; Schulman, 2020). The commercialization of GM crops, including maize, has been driven by the promise of increased yields, reduced pesticide use, and higher farmer profits (Klümper and Qaim, 2014; Brookes and Barfoot, 2018).

2.2 Global adoption rates and trends

Since its introduction, the adoption of GM maize has seen a rapid increase globally. By 2012, 88% of maize planted in the United States was genetically modified (Chavas et al., 2014). The global adoption of GM crops, including maize, has been significant, with GM varieties covering 13.5% of arable land worldwide by 2017 (Schulman, 2020). The economic benefits at the farm level have been substantial, with significant gains in yield and reductions in production costs (Brookes and Barfoot, 2015; Brookes and Barfoot, 2017; Brookes and Barfoot, 2018). However, the adoption rates vary significantly across different regions, with higher adoption in the Americas and lower rates in Europe and Africa due to regulatory and public acceptance challenges (Schulman, 2020; Aziz et al., 2022).

2.3 Regional case studies

United States: The United States has been a leader in the adoption of GM maize. By 2012, a vast majority of maize planted was genetically modified, driven by the technology's ability to increase yields and reduce the adverse effects of crop rotations (Chavas et al., 2014). The economic impact has been profound, with significant increases in farm income and reductions in pesticide use (Klümper and Qaim, 2014; Brookes and Barfoot, 2018).

Spain and Portugal: In Europe, Spain and Portugal have been notable for their adoption of GM insect-resistant maize. Since its introduction in 1998, GM maize has been planted on 1.65 million hectares, resulting in increased yields and significant reductions in insecticide use. The economic benefits for farmers in these countries have been substantial, with a notable increase in income and a reduction in the environmental impact of maize cultivation (Brookes, 2019).

Africa: The adoption of GM maize in Africa has been slower compared to other regions. However, the potential benefits are significant given the challenges of food insecurity and limited arable land. GM maize offers higher yields and could play a crucial role in addressing food shortages. Despite these benefits, concerns about health risks and environmental impacts have hindered widespread adoption. Continued research and regulatory approval are essential to address these concerns and facilitate the adoption of GM maize in Africa (Mwamahonje and Mrosso, 2016).

In summary, the historical context and adoption of GM maize highlight the technology's potential to enhance agricultural productivity and sustainability. While the global adoption rates and trends show significant progress, regional case studies underscore the varying levels of acceptance and the need for continued research and regulatory efforts to address concerns and maximize the benefits of GM maize in sustainable agriculture.

3 Agronomic Benefits of GM Maize

3.1 Yield improvements and stability

Genetically modified (GM) maize has demonstrated significant yield improvements and stability across various environments. A meta-analysis revealed that GM technology adoption has increased crop yields by an average of 22% globally, with higher gains observed in developing countries compared to developed ones (Klümper and Qaim, 2014). Additionally, the overexpression of the *zmm28* gene in maize has been shown to enhance grain yield consistently across different years and environments by improving plant growth, photosynthesis capacity, and nitrogen utilization (Wu et al., 2019). In Argentina, the introduction of GM insect-tolerant maize has allowed for optimized sowing dates, reducing the risk of water deficits and stabilizing yields across different rainfall gradients (Figure 1) (Otegui et al., 2021). Furthermore, empirical analysis in the United States has indicated that GM technology reduces the adverse effects of maize-maize rotation on yield, thereby offering good prospects for future productivity improvements (Chavas et al., 2014).

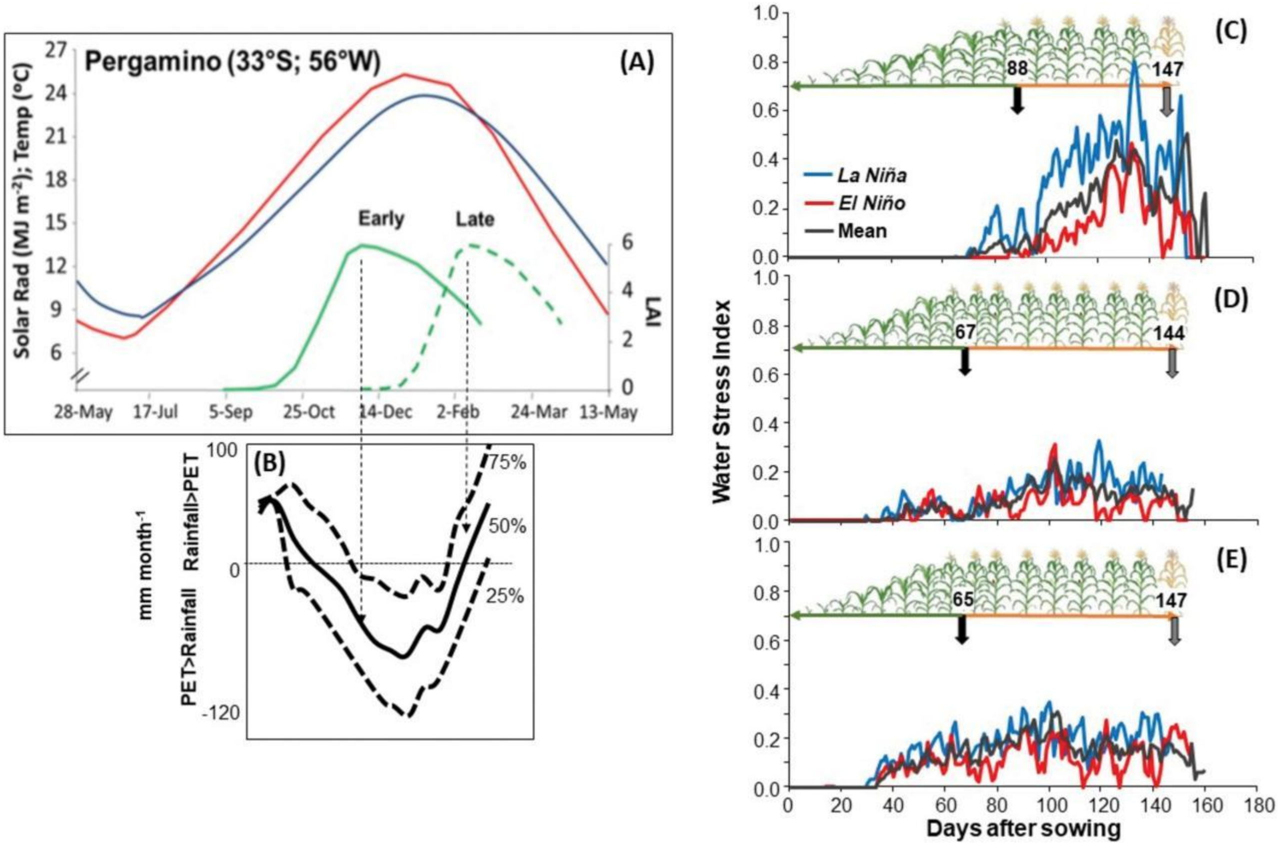

Figure 1 (A) Schematic representation of leaf area index (LAI) evolution (in green) for early- and late-sown maize crops in a representative location (Pergamino) of the Central humid region of Argentina. Mean historic values of incident solar radiation (Solar Rad) and air temperature (Temp) are shown in red and blue, respectively. (B) Water balance evolution for the same region, based on the difference between rainfall and potential evapotranspiration (PET) (Adopted from Otegui et al., 2021)

Image caption: Lines are representative of the median (50%) and the 25% and 75% percentiles. Vertical dashed arrows correspond to the estimated silking date of each crop in (A). (C-E) Water stress index for crop growth under dryland farming, obtained with the CERES-Maize model for a historic series of 41 climate records for Pergamino (1978-1979 to 2018-2019). Data represent the extreme phases of the ENSO phenomenon (La Niña and El Niño, with 14 years each) as well as mean values across all seasons. Vertical arrows indicate the median for silking (black) and physiological maturity (gray), together with the corresponding number of days after sowing. Horizontal arrows indicate the vegetative (green) and reproductive (orange) periods. (C) Sowing on 20 September with soil at field capacity up to 1.8 m depth. (D) Sowing on 10 Dec with soil as in (C). (E) Sowing on 20 December with the uppermost 60 cm soil layer at field capacity and the rest at 30% of plant-available soil water (Adopted from Otegui et al., 2021)

3.2 Reduction in pesticide use

The adoption of GM maize has led to a substantial reduction in pesticide use, contributing to more sustainable agricultural practices. On average, GM technology has reduced chemical pesticide use by 37% (Klümper and Qaim, 2014). Specifically, the introduction of Bt maize, which expresses insecticidal proteins from *Bacillus thuringiensis*, has significantly decreased the need for insecticides. This reduction in pesticide use has been particularly notable in the United States, where the use of insecticides on maize has declined substantially since the introduction of GM crops (Coupe and Capel, 2016). Additionally, the global adoption of GM crops has been estimated to reduce pesticide use by millions of kilograms annually, with significant environmental benefits such as reduced diesel consumption and lower carbon dioxide emissions (Phipps and Park, 2002).

3.3 Enhanced resistance to pests and diseases

GM maize varieties have been engineered to enhance resistance to pests and diseases, providing agronomic benefits and reducing crop losses. For instance, Bt maize has been effective in controlling the European corn borer, leading to areawide suppression of this pest and economic benefits for both Bt and non-Bt maize growers (Hutchison et al., 2010). In Mexico, GM insect-resistant maize hybrids have shown improved grain yield and resistance to target insect pests, offering an alternative for farmers to protect their crops from insect damage (Díaz et al., 2016). The enhanced resistance conferred by GM maize not only reduces the need for chemical pesticides but also contributes to more stable and higher yields, supporting sustainable agricultural practices.

4 Economic Impacts

4.1 Farmer income and profitability

The adoption of genetically modified (GM) maize has had a significant positive impact on farmer income and profitability. Studies have shown that GM technology adoption has increased farmer profits by 68% on average, with higher gains observed in developing countries compared to developed ones (Klümper and Qaim, 2014). Over the period from 1996 to 2020, the cumulative farm income gains from GM crop technology amounted to $261.3 billion, with an average farm income gain of about $112 per hectare (Brookes, 2022). These gains are attributed to both yield improvements and cost savings, with 72% of the benefits derived from yield and production gains and the remaining 28% from cost savings (Brookes and Barfoot, 2013; Brookes and Barfoot, 2015; Brookes and Barfoot, 2017; Brookes and Barfoot, 2018; Brookes and Barfoot, 2020; Brookes, 2022).

4.2 Cost-benefit analysis of GM maize adoption

A cost-benefit analysis of GM maize adoption reveals substantial economic benefits for farmers. For each extra dollar invested in GM crop seeds, farmers gained an average of $3.76 in extra income, with higher returns observed in developing countries ($5.22) compared to developed countries ($3.00) (Brookes, 2022). The technology has also led to significant reductions in chemical pesticide use, which decreased by 37% on average, contributing to cost savings and environmental benefits (Klümper and Qaim, 2014). Additionally, the adoption of GM maize has mitigated the adverse effects of maize-maize rotation on yield, further enhancing its economic viability (Chavas et al., 2014).

4.3 Market dynamics and trade

The widespread adoption of GM maize has influenced market dynamics and trade patterns. The increased production levels of GM maize have contributed to global food security by adding significant quantities to the global maize supply. For instance, since the mid-1990s, GM technology has added 595 million tonnes to the global production of maize (Brookes, 2022). This increased supply has implications for global trade, as countries with high adoption rates of GM maize can potentially export surplus production, thereby influencing global maize prices and trade flows. The economic benefits of GM maize adoption are shared between farmers in developed and developing countries, with a roughly equal distribution of gains (Brookes and Barfoot, 2013; Brookes and Barfoot, 2015; Brookes and Barfoot, 2017; Brookes and Barfoot, 2018; Brookes and Barfoot, 2020).

In summary, the adoption of GM maize has led to substantial economic benefits for farmers, including increased income and profitability, significant cost savings, and enhanced market dynamics and trade. These benefits underscore the potential of GM maize to contribute to sustainable agricultural practices and global food security.

5 Environmental Impacts

5.1 Reduction in chemical pesticide use and environmental benefits

The adoption of genetically modified (GM) maize has been shown to significantly reduce the use of chemical pesticides, leading to various environmental benefits. For instance, the use of insect-resistant GM maize in Spain and Portugal has resulted in a 37% reduction in insecticide spraying, which translates to a decrease of 678,000 kg of active ingredient over 21 years. This reduction has also led to a 21% decrease in the environmental impact associated with herbicide and insecticide use, as measured by the Environmental Impact Quotient (EIQ) (Brookes, 2019). Similarly, globally, GM crops have reduced pesticide use by 22.3 million kg of formulated product in the year 2000 alone, with significant reductions in the use of herbicides and insecticides for crops like soybean, oilseed rape, cotton, and maize (Phipps and Park, 2002). In China, the introduction of Bt maize has mitigated pest pressure without the need for synthetic insecticides, reducing mycotoxin contamination by 85.5%~95.5% and avoiding yield loss by 16.4%~21.3% (Yang et al., 2022).

5.2 Impact on biodiversity and ecosystem health

The impact of GM maize on biodiversity and ecosystem health is complex and multifaceted. Studies have shown that the environmental impact of herbicide regimes used with GM herbicide-resistant (GMHR) maize is generally lower than that of non-GMHR maize, primarily due to the lower potential of herbicides like glyphosate and glufosinate-ammonium to contaminate groundwater and their lower acute toxicity to aquatic organisms (Devos et al., 2008). However, the long-term effects on farmland biodiversity, such as shifts in weed communities and losses in food resources and shelter for non-target organisms, remain uncertain (Devos et al., 2008). Additionally, the introduction of GM crops can alter soil microbial communities, although these effects are often variable and transient. For example, while some studies have shown changes in soil metabolomes, the overall impact on rhizosphere bacterial communities appears to be minimal (Figure 2) (Chen et al., 2022). The adoption of GM crops has also been associated with changes in soil food web properties and crop litter decomposition, although these effects are inconsistent and often influenced by environmental factors such as precipitation (Powell et al., 2009).

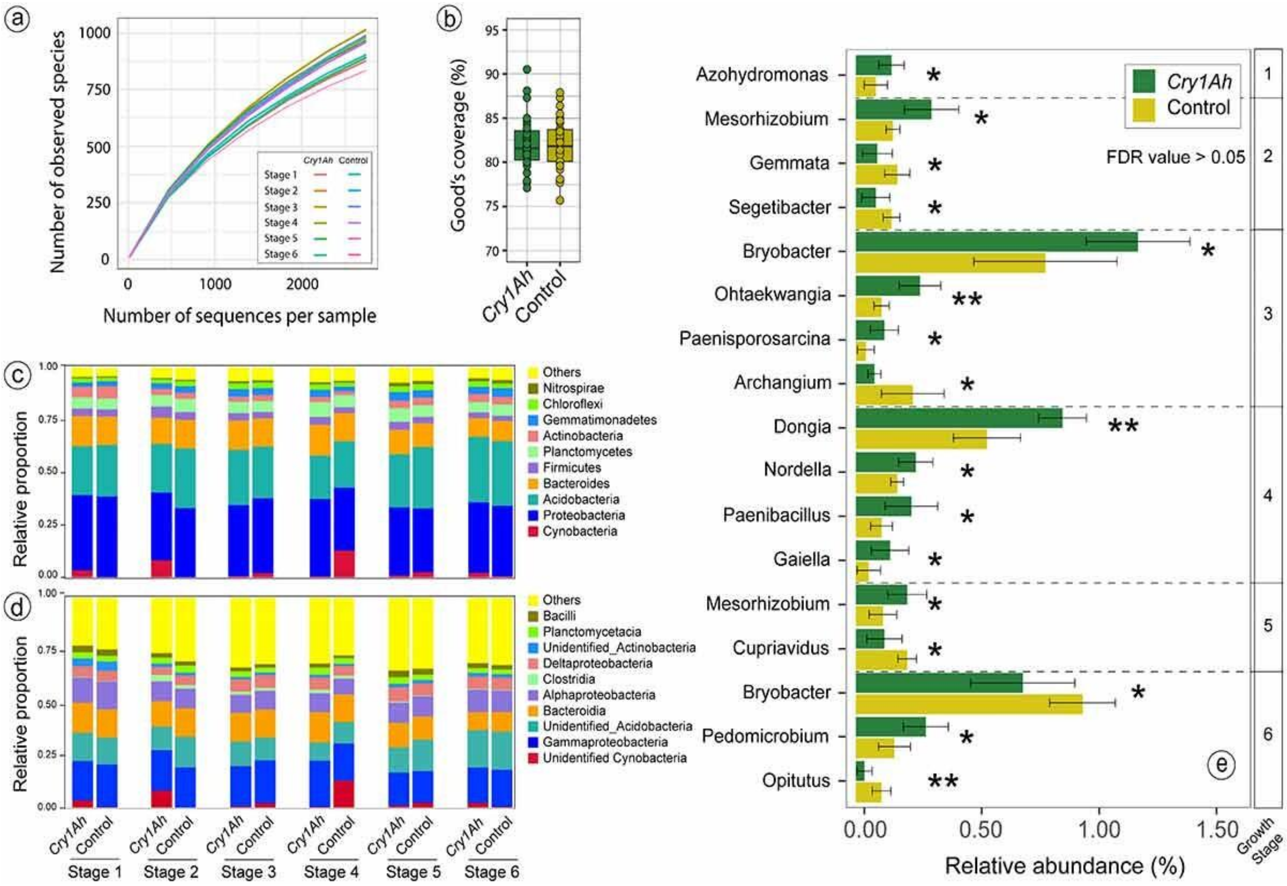

Figure 2 The composition of the rhizosphere bacterial community of insecticidal transgenic and control maize cultivars is estimated by amplicon sequencing (Adopted from Chen et al., 2022)

Image caption: (a) Rarefaction curves of the number of OTUs at the 97% sequence similarity of two cultivars at different growth stages. (b) Box plots showing the Good's coverage for the bacterial community in two cultivars. The relative contribution of top ten bacterial phyla (c) and classes (d) in two cultivars at different growth stages. (e) Differentially altered bacterial genera (relative abundance of 0.1% in at least one treatment) in the transgenic rhizosphere as compared to control maize at different growth stages based on student t-test (* denotes $P < .05$; and ** denotes $P < .01$). However, the FDR value for all the genera tested was more than 0.05, indicating that the bacterial composition was not different in transgenic maize and control (Adopted from Chen et al., 2022)

5.3 Soil health and water use

The cultivation of GM maize can have both positive and negative effects on soil health and water use. On the positive side, the reduced need for chemical pesticides can lead to lower levels of soil and water contamination, contributing to overall soil health. For example, the use of GM maize in broiler production in Argentina has been associated with lower impacts on global warming, ozone depletion, freshwater ecotoxicity, and human toxicity (Bennett et al., 2006). However, the impact of GM crops on soil microbial communities and nutrient cycling is still not fully understood. Some studies have shown that transgenic plants can release novel proteins into the soil ecosystem, potentially influencing microbial biodiversity and ecosystem functioning (Dunfield and Germida, 2004). Additionally, the management practices associated with GM crops, such as the use of specific herbicides, can affect soil biota and crop litter decomposition, although these effects are often transient and influenced by environmental conditions (Powell et al., 2009).

In summary, the use of genetically modified maize in sustainable agriculture offers significant environmental benefits, particularly in reducing chemical pesticide use and associated environmental impacts. However, the long-term effects on biodiversity, ecosystem health, soil health, and water use require further study to fully understand and mitigate potential risks.

6 Technological Advances in GM Maize

6.1 Advances in transformation techniques and genome editing

The development of genetically modified (GM) maize has seen significant advancements in transformation techniques and genome editing. Traditional transformation methods have evolved, incorporating morphogenic regulators to increase transformation frequency and genotype independence. Emerging technologies such as RNA-guided endonuclease systems, double haploid production, and pollen transformation have further enhanced the efficiency and precision of maize transformation (Yassitepe et al., 2021). The CRISPR/Cas9 platform, in particular, has revolutionized genome editing by enabling precise modifications without incorporating transgenic elements, thus addressing many concerns associated with GM crops and facilitating their acceptance and commercialization (Figure 3) (Aziz et al., 2022; Hernandes-Lopes et al., 2023).

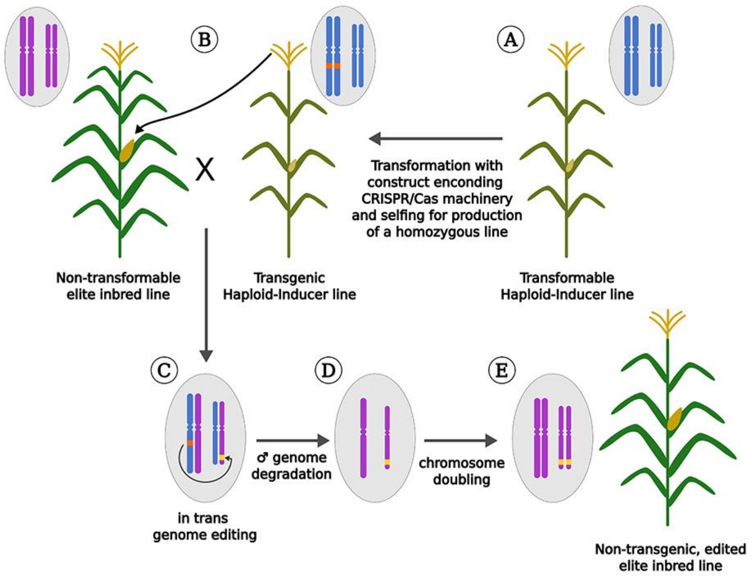

Figure 3 *In trans* genome editing in maize (Adopted from Hernandes-Lopes et al., 2023)

Image caption: First, a haploid-inducer (HI) line (amenable to transformation) is equipped with the CRISPR/Cas machinery targeting a specific locus (A). Next, HI pollen is used to pollinate plants from a non-transformable genotype (B). After fertilization, the CRISPR/Cas machinery encoded by the male parental genome edits the female genome (C). The male genome is degraded, resulting in a haploid embryo containing only the female genome (D). Chromosome doubling is achieved by applying chemical agents, resulting in a non-transgenic double haploid plant harboring the edited female genome (E) (Adopted from Hernandes-Lopes et al., 2023)

6.2 Development of new traits and varieties

The introduction of GM technology has led to the development of maize varieties with enhanced traits such as herbicide resistance, insect resistance, and tolerance to abiotic stresses like drought and heat. These traits have significantly improved maize yield and resilience, making it a crucial crop for food security and sustainable agriculture (Zafar et al., 2019; Yassitepe et al., 2021). Additionally, GM maize varieties have been developed to improve nutritional quality and other agronomic traits, contributing to the overall productivity and sustainability of agricultural systems (Zafar et al., 2019; Sharma et al., 2022).

6.3 Integration with other agricultural technologies

The integration of GM maize with other agricultural technologies has further amplified its benefits. For instance, GM technology has been shown to complement crop rotation practices, reducing the adverse effects of continuous maize cultivation and enhancing yield gains associated with higher planting densities (Chavas et al., 2014). Moreover, the combination of GM maize with precision agriculture tools and sustainable farming practices can optimize resource use, reduce environmental impact, and increase overall agricultural efficiency (Yassitepe et al., 2021; Sharma et al., 2022). This holistic approach to integrating GM maize with other technologies underscores its potential in achieving sustainable agricultural goals.

7 Case Study

7.1 Detailed examination of GM maize use in a specific region

In Mexico, the adoption of genetically modified (GM) maize hybrids has been studied extensively. Specifically, the environmental risk assessment (ERA) of GM maize hybrids MON-89×34-3 × MON-88×17-3, MON-89×34-3 × MON-Ø86×3-6, and MON-Ø86×3-6 was conducted across five ecological regions from 2009 to 2013. These hybrids were compared with conventional maize hybrids of similar genetic backgrounds. The studies revealed that the GM hybrids did not differ significantly from conventional maize in terms of early stand count, days-to-silking, days-to-anthesis, root lodging, stalk lodging, or final stand count. However, differences were noted in seedling vigor, ear height, plant height, grain moisture, and grain yield, particularly in the insect-resistant (IR) hybrids (Díaz et al., 2016).

7.2 Analysis of agronomic, economic, and environmental outcomes

7.2.1 Agronomic outcomes

The adoption of GM maize in Mexico showed that the IR hybrids had higher grain yield and grain moisture compared to conventional hybrids. These phenotypic differences, however, were not expected to contribute to increased pest potential or ecological risk. The GM hybrids demonstrated similar agronomic performance to conventional maize, confirming their suitability for cultivation without additional risks (Díaz et al., 2016).

7.2.2 Economic outcomes

In Colombia, the use of GM maize has led to significant economic benefits. Farmers experienced an increase in income of US $301.7 million over fifteen years. For every extra US $1 spent on GM seed relative to conventional seed, farmers gained an additional US $5.25 in extra income from growing GM maize. These income gains were primarily due to higher yields, with GM maize showing a 17.4% increase in yield compared to conventional maize (Table 1) (Brookes, 2020).

Table 1 Farm income gains derived from GM cotton and maize (‘US million $) (Adopted from Brookes, 2020)

Country	2018	Cumulative	Cumulative area planted to GM crops (’000 ha)
Maize	14.59	188.11	718 940
Cotton	4.37	113.55	354 460
Total	18.96	301.66	1 073 400

7.2.3 Environmental outcomes

The environmental impact of GM maize in Colombia included a reduction in insecticide and herbicide spraying by 779 400 kg of active ingredient, which is a 19% decrease. This reduction in chemical use also led to a 26% decrease in the Environmental Impact Quotient (EIQ), indicating a lower environmental footprint. Additionally, the technology facilitated cuts in fuel use, resulting in reduced greenhouse gas emissions from the GM maize cropping area (Table 2) (Brookes, 2020).

Table 2 Impact of using GM maize and cotton in Colombia: changes in insecticide use and associated environmental impact (as measured by EIQ indicator) 2003~2018 (Adopted from Brookes, 2020)

Trait	Change in volume of active ingredient used ('000 kg)	Change in field EIQ impact (in terms of million field EIQ/ha units)	Percent change in active ingredient use on GM crops	Percent change in environmental impact associated with insecticide use on GM crops
IR maize	−279.4	−7.0	−66	−65
HT maize	−278.5	−10.4	−13	−22
IR cotton	−176.5	−7.1	−25	−27
HT cotton	−45.1	−0.7	−5	−5
Total	−779.4	−25.2	19	26

7.3 Lessons learned and best practices

The case studies from Mexico and Colombia provide several key lessons and best practices for the use of GM maize in sustainable agriculture:

Yield improvement: GM maize hybrids, particularly those with insect-resistant traits, can significantly increase crop yields. This is crucial for improving food security and farmer income, especially in developing countries (Díaz et al., 2016; Brookes, 2020).

Economic benefits: The adoption of GM maize can lead to substantial economic gains for farmers. The increased income from higher yields and reduced costs associated with pesticide use make GM maize a financially viable option (Brookes, 2020).

Environmental sustainability: The reduction in pesticide use and the associated decrease in environmental impact highlight the potential of GM maize to contribute to more sustainable agricultural practices. This includes lower greenhouse gas emissions and reduced chemical runoff, which are beneficial for the environment (Brookes, 2020).

Risk assessment and management: Comprehensive environmental risk assessments are essential to ensure that GM crops do not pose additional risks compared to conventional crops. The studies in Mexico demonstrated that GM maize hybrids could be cultivated without increasing pest potential or ecological risks (Díaz et al., 2016).

Regulatory framework: A conducive regulatory environment is necessary to facilitate the adoption of GM crops. Overregulation can hinder the potential benefits of GM technology, particularly in developing countries where the need for improved agricultural productivity is greatest (Qaim, 2009).

By integrating these lessons and best practices, regions considering the adoption of GM maize can maximize the agronomic, economic, and environmental benefits while minimizing potential risks.

8 Regulatory and Public Perception

8.1 Overview of regulatory frameworks for GM crops

The regulatory frameworks for genetically modified (GM) crops are designed to ensure their safety for human consumption and environmental impact. These frameworks involve rigorous testing and evaluation processes before GM crops can be approved for commercial use. Regulatory bodies such as the United States Department of Agriculture (USDA), the Environmental Protection Agency (EPA), and the Food and Drug Administration (FDA) in the United States, as well as similar organizations in other countries, play crucial roles in this process. They assess various factors, including potential allergenicity, toxicity, and environmental effects, to ensure that GM crops do not pose any significant risks (Halford and Shewry, 2000; Aziz et al., 2022). The legal requirements for containment and the roles of these regulatory bodies are essential in maintaining public trust and ensuring the safe deployment of GM crops in agriculture (Halford and Shewry, 2000).

8.2 Public perception and controversies surrounding GM maize

Public perception of GM maize is mixed and often polarized. While some view GM crops as a technological advancement that can address food security and agricultural sustainability, others express concerns about their long-term health and environmental impacts. The controversies surrounding GM maize include fears of cross-pollination with non-GM crops, the introduction of new allergens, and the potential for antibiotic resistance marker genes to affect human health (Halford and Shewry, 2000). Additionally, there is a significant debate on the ethical implications of modifying the genetic makeup of crops and the potential monopolization of seed markets by large biotech companies (Halford and Shewry, 2000; Aziz et al., 2022). These concerns have led to widespread hostility and calls for more transparent communication and rigorous scientific investigations to address public fears and misconceptions (Aziz et al., 2022).

8.3 Ethical and social considerations

The ethical and social considerations of using GM maize in sustainable agriculture are multifaceted. Ethical concerns revolve around the manipulation of natural organisms and the potential unforeseen consequences of genetic modifications. There is also a moral debate on the right to modify the genetic structure of living organisms for human benefit (Aziz et al., 2022). Socially, the adoption of GM maize can have significant implications for smallholder farmers, particularly in developing countries. Issues such as seed sovereignty, dependency on biotech companies for seeds, and the potential displacement of traditional farming practices are critical considerations (Halford and Shewry, 2000; Aziz et al., 2022). Addressing these ethical and social issues requires a balanced approach that considers both the potential benefits of GM maize in enhancing food security and the need to respect and preserve traditional agricultural practices and biodiversity (Aziz et al., 2022).

9 Challenges and Limitations

9.1 Potential risks and health concerns

The adoption of genetically modified (GM) maize has raised several potential risks and health concerns. One of the primary concerns is the long-term impact of GM crops on human health, which remains a contentious issue due to the lack of conclusive long-term studies. Additionally, there are fears about the potential for GM crops to cause allergic reactions or transfer antibiotic resistance markers to humans (Azadi et al., 2015). Environmental risks, such as the unintended harm to non-target species and the potential for GM crops to crossbreed with wild relatives, further complicate the debate (Azadi et al., 2015).

9.2 Overregulation and its impact on innovation

Overregulation of GM crops can stifle innovation and slow the adoption of beneficial technologies. Regulatory frameworks in many countries are stringent, requiring extensive testing and approval processes that can be both time-consuming and costly. This can deter investment in GM research and development, particularly for small and medium-sized enterprises that may lack the resources to navigate complex regulatory landscapes (Azadi et al., 2015). The high costs associated with meeting regulatory requirements can also limit the availability of GM seeds to farmers, particularly in developing countries where regulatory barriers are often higher (Azadi et al., 2015).

9.3 Socio-economic barriers to adoption

Socio-economic barriers significantly impact the adoption of GM maize, especially among small-scale farmers. The high cost of GM seeds and the associated intellectual property rights can make it difficult for resource-poor farmers to access these technologies (Azadi et al., 2015). Additionally, there is often a lack of adequate information and extension services to educate farmers about the benefits and proper use of GM crops, leading to low adoption rates (Azadi et al., 2015). Socio-economic concerns also include the potential for GM crops to exacerbate existing inequalities in the agricultural sector, as wealthier farmers are more likely to afford and benefit from these technologies (Azadi et al., 2015).

10 Future Prospects and Recommendations

10.1 Potential future developments in GM maize technology

The future of genetically modified (GM) maize technology holds significant promise for enhancing agricultural productivity and sustainability. Advances in biotechnology, such as CRISPR/Cas9 genome editing, are expected to play a pivotal role in developing maize varieties with improved traits, including higher yields, enhanced nutritional quality, and increased resistance to biotic and abiotic stresses (Yassitepe et al., 2021; Aziz et al., 2022). Emerging technologies, such as tissue culture-independent methods and RNA-guided endonuclease systems, are anticipated to streamline the transformation process, making it more efficient and genotype-independent (Yassitepe et al., 2021). These innovations could lead to the development of maize varieties that are better suited to diverse environmental conditions, thereby contributing to global food security and sustainable agriculture (Qaim, 2009; Klümper and Qaim, 2014).

10.2 Recommendations for policy and practice to enhance sustainable agriculture

To maximize the benefits of GM maize technology, it is crucial to implement policies and practices that support sustainable agriculture. Policymakers should focus on creating a conducive regulatory environment that balances safety concerns with the need for innovation. Overregulation can hinder the development and adoption of GM crops, particularly in developing countries where the potential benefits are substantial (Qaim, 2009; Sharma et al., 2022). It is essential to design efficient regulatory mechanisms that facilitate the approval and commercialization of GM crops while ensuring environmental and human health safety (Sharma et al., 2022).

Additionally, integrating GM maize into sustainable agricultural practices requires promoting best management practices, such as crop rotation and optimized planting densities, to enhance yield gains and reduce risks (Chavas et al., 2014). Public awareness campaigns and educational programs can help address public reservations and increase acceptance of GM technology by highlighting its benefits for food security, environmental sustainability, and economic growth (Klümper and Qaim, 2014; Brookes, 2022).

10.3 Integration with global sustainability goals

The integration of GM maize technology with global sustainability goals, such as the United Nations Sustainable Development Goals (SDGs), is vital for achieving long-term agricultural sustainability. GM maize can contribute to several SDGs, including zero hunger (SDG 2), good health and well-being (SDG 3), and climate action (SDG 13) (Otegui et al., 2021; Aziz et al., 2022). By increasing crop yields and reducing the need for chemical pesticides, GM maize can help alleviate food insecurity and improve nutritional outcomes (Klümper and Qaim, 2014; Brookes, 2022). Moreover, the adoption of GM maize with traits such as drought tolerance and nitrogen-use efficiency can mitigate the impacts of climate change and reduce the environmental footprint of agriculture (O'Brien and Mullins, 2009; Otegui et al., 2021).

To fully realize these benefits, it is important to foster international collaboration and knowledge sharing among researchers, policymakers, and farmers. This collaborative approach can facilitate the development and dissemination of GM maize technologies that are tailored to local conditions and needs, thereby enhancing their effectiveness and sustainability (O'Brien and Mullins, 2009; Aziz et al., 2022). By aligning GM maize technology with global sustainability goals, we can create a more resilient and sustainable agricultural system that benefits both current and future generations.

11 Concluding Remarks

The adoption of genetically modified (GM) maize has shown significant positive impacts on maize yield and agricultural management. Studies indicate that GM technology has increased maize yield by reducing exposure to downside risks and enhancing the benefits of higher planting densities. Additionally, GM maize varieties have been developed to incorporate traits such as herbicide and insect resistance, abiotic stress tolerance, and improved nutritional quality, which have collectively contributed to higher productivity and better crop management. In regions like Spain and Portugal, the use of GM insect-resistant maize has led to substantial economic benefits, including increased farmer income and reduced insecticide use, thereby lowering the environmental impact.

Furthermore, environmental risk assessments have confirmed that GM maize hybrids do not pose additional risks compared to conventional maize, making them a viable alternative for sustainable agriculture.

The integration of GM maize into agricultural practices has several implications for sustainable agriculture. Firstly, the increased yield and reduced need for chemical inputs such as insecticides and herbicides contribute to more efficient resource use and lower environmental footprints. This aligns with the goals of sustainable agriculture, which seeks to balance productivity with environmental stewardship. Moreover, the development of GM maize varieties that are resistant to pests and tolerant to abiotic stresses can help mitigate the impacts of climate change and ensure food security in regions with challenging growing conditions. The ability of GM maize to substitute for traditional crop rotation practices also offers flexibility in crop management, potentially leading to more sustainable land use.

Genetically modified maize plays a crucial role in advancing sustainable agriculture by enhancing crop yields, reducing the need for chemical inputs, and providing resilience against environmental stresses. While there are concerns regarding the potential health and environmental risks associated with GM crops, extensive research and regulatory assessments have generally supported their safety and efficacy. As the global population continues to grow and the demand for food increases, GM maize offers a promising solution to meet these challenges sustainably. Future research should continue to address the potential risks and explore new biotechnological advancements to further improve the sustainability and acceptance of GM maize in agriculture.

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Conflict of Interest Disclosure
Author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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