Narrative Review Article

Genetically Modified Crops and Sustainable Food Systems

Pragna Patlola[1], Kyle Wan[2], Khushi Gehani[3], Shriya Lingineni[4], Tarit Voni[5]

[1]Portola High School, 112 Pixel, Irvine, CA 92618, United States; [2]Fairmont Preparatory Academy, 18622 Mesa Drive, Villa Park, CA 92861, United States; [3]Oxford Academy, 5611 Pineridge Drive, La Palma, CA 90623, United States; [4]Fairmont Preparatory Academy, 12514 Rose Street, Cerritos, CA 90703, United States; [5]Trabuco Hills High School, 22061 Teresa, Mission Viejo, CA 92692, United States

ABSTRACT

Genetically modified organisms (GMOs) offer a potential economically and logistically viable solution to a global problem: feeding a growing global population under worsening climate conditions. GMOs can be engineered to withstand environmental stress, resist disease, and improve nutritional value while maintaining safety comparable to conventional foods. Already, GMOs have contributed to substantial global yield gains by reducing crop losses from pests and environmental stress across widely cultivated staple crops. Despite this, public skepticism persists regarding GMOs' safety, nutritional quality, and dependence upon multinational corporations, especially in parts of Europe where GMO adoption and trade remain restricted. Despite GMOs' controversy and sociopolitical barriers to adoption, this report finds that existing literature broadly agrees that GMOs can serve as a safe, economically viable, and sustainable response to climate and food-scarcity challenges.

Keywords: GMO; Genetically Modified Crops; Agriculture; Agrotechnology; Organic Crops

INTRODUCTION

The 1990s marked a new era of agricultural technology that promised to transform age-old methods of growing, distributing, and consuming food. At a time of rising international concern about food scarcity and economic and environmental sustainability. Two sides of a global debate on this technology, the ability to genetically modify crops, arose: some believed it would be a defining innovation to address the future of our global food system; others believed it posed risks to health or the economic independence of local farmers.

GMO crops are plants whose DNA has been altered to express traits that do not occur naturally in that particular species. GMO crops are modified to display traits such as pest resistance, herbicide-resistant, potential to provide enhanced nutritional value, and an extended shelf life (1). GMO crops, GM crops, and genetically modified crops are all interchangeable with this same meaning. These biological inventions increase the ability of crops to tolerate environmental stresses and provide food to a growing population of human beings, and they provide a contribution to a solution for global food security. This paper will explore whether GMOs can serve as a sustainable solution to food insecurity in the face of climate change, economic and sociopolitical challenges, and growing populations.

Corresponding author: Pragna Patlola, E-mail: Patlolapragna06@gmail.com.

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AGRONOMIC IMPACTS

The adoption of GMO crops, particularly pest and disease resistance crops, has significantly increased farming outputs. Klumper and Qaim's literature analysis (147 studies) suggest that Bt crops increased yield by 24% and reduced insecticide use by 37% based on farm-level and field-trial data collected from the mid-1900s through the early 2010s, comparing Bt crops to non-GM counterparts grown during the same production seasons (2). This insect resistance benefit can be seen globally as crops such as Bt corn show consistent yield advantages over non-Bt corn in the Philippines, the United States, and in a multi country analysis (Figure 1). Heightened yields address food-scarcity challenges by strengthening the global food supply and reducing crop cycle losses. Across regions and crop types, this study supports yield stability as one of the most empirically verified benefits of GMOs.

It is possible, however, that the widespread use of GMO crops exerts selective pressure on certain pests populations, leading to the evolution of resistance and risking an arms race between biotechnology and insects. A review by Tabashnik and others (77 studies) presents findings of reduced efficiency of Bt crops connected to 5 of 13 major pest species including the Helicoverpa Zea (5). However, the same study goes on to rebut that innovation in multi-gene Bt crops prolong durability and reduce resistance evolution among pest populations. Despite the risk of reduced efficiency of pest-resistant GMO crops, which would consequently maintain yield losses, studies broadly confirm that the improvements in agrotechnology verify the long-lasting nature of these benefactors to food instability.

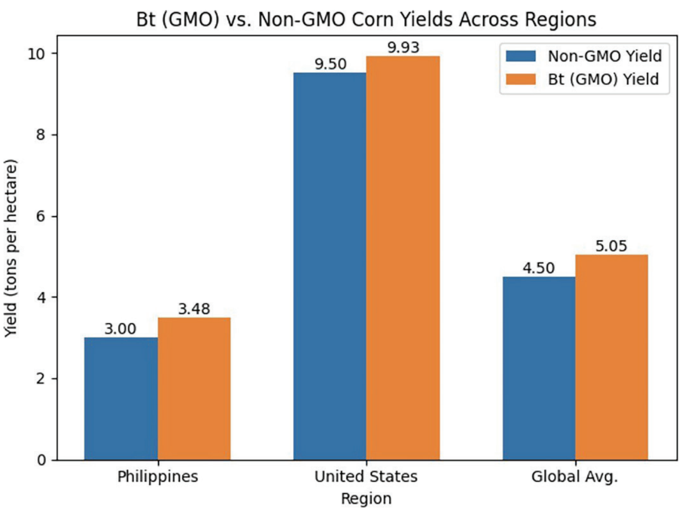

Figure 1. *GMO vs. Non-GMO Corn Yields Across Regions (Philippines, United States, Global Average). Representative average corn yields for GMO and non-GMO corn were compiled from multiple geographic datasets. Philippine yield values reflect national rate of yield post Bt corn introduction in 2002, using data from the USDA Foreign Agricultural Service (FAS) (3). An increase in U.S. yield values due to a reduction in pests as well as global averages summarizing increasing Bt corn performance were derived from a peer review article in the Cambridge University Press (4). This grouped bar chart illustrates that Bt corn yields are higher than non-GMO corn across diverse agricultural contexts.*

In addition to protecting yields, herbicide-tolerant GMO crops can contribute to improved soil conservation by enabling conservatory tilling practices. A study conducted in Nebraska discovered that crops such as glyphosate-tolerant soybeans allow farmers to control weeds chemically rather than through repeated plowing, reducing soil disturbance and erosion while allowing crops residues, an indicator of soil health, to remain on the field surface (6). This study has shown that conservation tillage systems, which can only be practiced with herbicide-tolerant GMO crops, increase soil minerals and reduce erosion compared to conventional tillage methods. As a result, these GMO crops enable agricultural practices that support long-term soil conservation and sustainability, promoting more yields on the same land.

On the other hand, similar to how pests gain resistance to GMO crops, weeds near herbicide-tolerant GMO can also develop resistance to herbicides. A comprehensive review of the use of glyphosate, a type of herbicide, found that extensive adoption of glyphosate-tolerant crops has led to the evolution of dozens glyphosate-resistant weed species worldwide (7). As resistant weeds become more common, herbicide-tolerant crops become less effective, and farmers may apply higher doses of herbicides to maintain crop yields. Despite these GMO crops initially having improved weed-control efficiency, studies warn that their continued adoption can create long-term weed management challenges, meaning that caution and further research are needed prior to adopting this solution on a global scale.

HEALTH IMPACTS

Another benefit of GMO crops is that their enhanced nutrient profiles reduce deficiency diseases, especially in populations that largely rely on a single staple crop. As the technology has grown, GMO crops have proven to improve not only food stability but also nutritional quality by increasing levels of essential nutrients such as vitamin A, vitamin E, folate, fiber, iron, zinc, and essential amino acids. A major example of this is Golden Rice, a genetically modified rice developed to combat vitamin A deficiency. Golden Rice has been proven to deliver sufficient beta carotene to significantly reduce vitamin A deficiency which can cause blindness and weakened immune systems (8). This is especially important in regions where rice is a dominant staple food and dietary diversity is limited. Additionally, GM cassava enriched with iron and zinc helps reduce anemia and support development (9). On the other hand, GM rice with increased folate content helps prevent birth defects and supports cell growth (10). Studies agree that this example suggests that these nutritional improvements are cost-effective and accessible, making GMO biofortification an effective solution for preventing malnutrition in low-income communities where supplements or fortified foods are often unaffordable (11).

Furthermore, changing the fatty acid composition of GMO crops leads to better heart health. Some GMO crops have been engineered to reduce unhealthy saturated and trans fats while increasing beneficial unsaturated fats such as omega 3 and omega 6 fatty acids (12). These modifications improve cholesterol levels and reduce the risk of cardiovascular disease. This is especially important because heart disease is a major global health risk, and trans fats are strongly linked to heart attacks and strokes. By producing healthier oils directly within crops, GMOs reduce reliance on chemical processing and provide a safer alternative for improving dietary fat consumption (13).

In addition to increasing the presence of beneficial compounds, GMOs also reduce exposure to toxins, lessening health complications associated with growing and consuming staple crops. Certain GMO foods have been developed to reduce natural toxins and allergens, such as low-allergen peanuts and low-cyanide cassava (14). Cassava naturally contains cyanogenic compounds that can be dangerous if improperly processed, so reducing these toxins increases food safety and availability, especially in regions that rely on cassava as a staple crop. Alongside reducing toxins within crops themselves, GMO pest-resistant crops reduce the need for chemical pesticides, which are harmful to not only the environment but also human health. In the Philippines, pesticide exposure among corn farmers has been linked to severe health effects including death, neuropathy, and long-term neurobehavioral damage (15). By adopting GMO corn that resists pests naturally, farmers lower their exposure to toxic chemicals through reduced pesticide use. This reflects the idea that pesticides harm not just crops but also the populations responsible for producing those crops, and GMOs help protect both farmers and consumers.

CLIMATE IMPACT

Modifications targeting water and heat stress lead to climate resilient crops. As GMO technology has expanded, crops have been engineered to improve tolerance to drought and extreme heat, allowing them to maintain yields under limited water availability. Drought tolerant GMO maize demonstrated higher yields under water stressed conditions compared to conventional crops, improving food stability in regions heavily affected by climate change, particularly Sub-Saharan Africa (16). Studies agree that this increased resilience helps reduce year-to-year crop failure in areas where agriculture depends on rainfall and drought can directly lead to food insecurity. However, drought tolerance is controlled by many genes rather than a single trait, meaning genetic modification often results in modest yield improvements rather than complete protection from drought (17). Despite this limitation, even small gains in yield and stability can have a significant impact in drought prone regions, where maintaining partial harvests helps prevent food shortages and supports long term climate adaptation.

Herbicide tolerance leads to carbon and moisture retention for soil, which directly reduces the need for fuel-heavy farming practices. This is evident as herbicide-tolerant crops decrease mechanical field passes, lowering fuel use and greenhouse emissions (18). Improved soil carbon and moisture retention and reduced fuel use offer a two-pronged method of targeting climate change. Overall, this study shows that herbicide tolerance fosters multiple benefits for both agricultural efficiency and the climate, including enhanced soil health, lower greenhouse gas emissions, and reduced energy use associated with farming tools.

Reducing the use of pesticides and fungicides lowers emissions associated with crop production, making agriculture more environmentally sustainable. To limit the need for fungicides or pesticides, a strand of GMO was produced to actively combat pests or fungi without the help of external media. Studies claim that since the initial introduction of GM crops, global pesticide use has been reduced by nearly 8.2% overall (2). Consequently, a study on the environmental impact of pesticide use estimates that the introduction of GMOs has reduced greenhouse gas emissions equivalent to those produced by 15 million cars (Figure 2). By reducing pesticide and fungicide use, GMOs help lower greenhouse gas emissions, contributing to efforts to mitigate climate change.

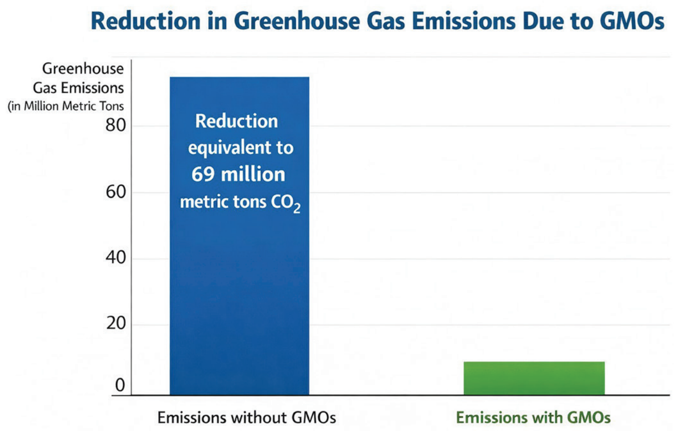

Figure 2. *Greenhouse Gas Emissions reduction from GMOs. Reduction in greenhouse gas emissions from crop production due to GMOs is estimated at 69 million metric tons of CO2, roughly equivalent to the annual emissions of 15 million passenger vehicles (18, 19).*

ECONOMIC IMPLICATIONS

Farmers who used GMOs experienced increased yield and reduced expenses. This is largely due to the lack of pesticide usage, which led to a total higher profit return compared to that of farmers not using GMOs. The Philippines is a prime example of this increase in profit: a study spanning multiple years indicated that approximately 460,000 farming families experienced benefits from GM corn from 2002 to 2019, illustrated by improvements in welfare for all income levels, with self-identified poorest households experiencing large proportional gains (20). More specifically, farmers in the Philippines using the Bt maize from 2004 to 2012 earned 7,964.31 more pesos, or 444.72 U.S. dollars, per month than farmers using hybrid breeds of corn (21).

On a global scale, farmers' gross incomes have increased by about US $261.3 billion cumulatively from 1996 to 2020 due to GM crop adoption (22). Studies across multiple scales of analysis therefore suggest that GMO crops both stabilize and increase farmer income. A portion of this increased income comes from GMOs lowering labor and fuel costs. The aforementioned herbicide resistance allows farmers to use alternative farming on the soil that often requires less fuel. Using a no-tillage system in farming GMO soybeans has been proven to save 27.12 liters of fuel per hectare of land, while a typical 90-foot herbicide sprayer needs 0.84 liters of fuel per hectare of land (23). Farmers save hundreds of liters of fuel per season with GMOs while also having to do less labor.

However, while GMOs exhibit multifaceted economic benefits, manufacturing complexity and patents lead to GMOs being tied to multinational corporations. The "Big Four" seed companies (Bayer/Monsanto, Corteva, Syngenta/ ChemChina, and BASF) control 56% of the global commercial seed market and 75% of the GMO seed traits (24). These companies are able to abuse their seed patent rights to sue farmers for re-distribution and charge royalties for usage. Between 1997 and 2010, Monsanto (now part of Bayer) filed 144 patent-infringement lawsuits against farmers (25). This legal pressure forces many farmers to pay royalties rather than risk costly judgments. Yet, those royalties still harm farmers; for example, Monsanto charges a 2% royalty on any GM soybean crop revenue in Brazil. Ultimately, GMOs threaten farmers' independence and present an opportunity for large companies to monopolize the seed market through patents.

SOCIOPOLITICAL BARRIERS

Misinformation and misunderstandings have led populations to believe that GMOs are unsafe. For example, when the World Health Organization was asked, "Why have there been concerns about GM foods among some politicians, public interest groups, and consumers?" They explained that decreased consumer confidence in food safety in Europe, caused by a series of unrelated food scares in the 1990s, has influenced skepticism towards GM foods over the years. This indicates that political concerns about GMOs are generally not based on actual risks but rather on lingering public doubt which originated during past food-safety issues (26). Still, regulatory hurdles create significant barriers to GMO adoption globally. In Africa, for example, adoption of GMOs has slowed due to the biosafety legislation and trade concerns (27). These legal and economic concerns make it difficult for farmers to obtain GMO seeds and for countries to approve their usage, slowing national adoption. Furthermore, Europe applies the Precautionary Principle due to past crises involving mad cow disease and dioxin contamination (28). Despite sound scientific backing, national fear forced European regulators to remain cautious. Ironically, these regulatory challenges are especially hindering in regions that are most strongly affected by climate change, where GMO crops could provide important resistance benefits.

Public concerns and skepticism toward GMOs play roles that motivate scientific research for potential harms. Public concerns relating to health impacts and environmental effects cause researchers to examine GMOs in a more comprehensive manner. Generally, these tests confirm the safety and reliability of GMOs directly to the public. A review inspected 204 studies that investigated the effects of GMOs on animals in 203 studies and humans in one trial. The authors of these studies reported adverse effects, especially those in animal trials, such as mortality, tumor or cancer, and organ abnormalities.

However, these effects were only seen in a small group of animal studies: 7.84% (29). In the human trial, only minor effects were recorded. However, the overall conclusion of the systematic review was that the studies were unclear and had a high risk of bias. As there was no consistent pattern of harm, any conclusions of harm did not display convincing causation. The studies of many major scientific organizations, like the WHO, FAO, EFSA, and NAS, all concluded that there are no unique health risks of GMO food.

CONCLUSION

This narrative review synthesizes agronomic, environmental, nutritional, economic, and sociopolitical literature on genetically modified (GM) crops to evaluate their role in agricultural sustainability. Across agronomic and climate-focused studies, there is strong evidence that GM crops—particularly Bt and herbicide-tolerant varieties—enhance yield stability while reducing reliance on chemical inputs such as pesticides, herbicides, and intensive tilling. These practices contribute to soil conservation and lower environmental footprints. Nutritional research further indicates that certain GM foods can improve micronutrient content, reduce allergens, and enhance dietary quality. Large-scale scientific assessments, including analyses of regulatory and academic consensus reports, consistently conclude that GMOs do not pose substantiated health risks.

Despite these benefits, literature also highlights persistent challenges. Pest resistance, while often cited as a major drawback, is a known evolutionary process and can be mitigated through strategies such as refuge planting and crop rotation. Many of the socioeconomic concerns surrounding GMOs—such as farmer dependency and market concentration—stem more from policy and corporate practices than from genetic technologies themselves. Public skepticism remains a significant barrier, often driven by concerns over corporate influence, transparency, and long-term safety. A key limitation of the current literature is its reliance on short-term studies, frequently restricted to single growing seasons. This constrains understanding of long-term ecological effects, biodiversity impacts, multi-generational health outcomes, and potential risks such as horizontal gene transfer. Independent research on newer gene-editing technologies, including CRISPR-based traits, remains limited. Furthermore, much of the existing evidence is regionally concentrated. While GM crop adoption has demonstrated success in places such as the Philippines, these outcomes may not generalize to all agricultural systems, climates, or socioeconomic contexts. There is a pressing need for long-term, independent studies, particularly in low-income regions, to evaluate sustained nutritional, economic, and environmental effects.

Overall, the evidence suggests that GM crops offer substantial promise for enhancing food security, improving climate resilience, and stabilizing agricultural markets. At the same time, non-GMO systems underscore the importance of preserving biodiversity, respecting traditional agricultural practices, and limiting overreliance on multinational corporations. Future research should prioritize longitudinal field studies, transparent regulatory evaluation, and inclusive public engagement. Such efforts will be critical for determining how genetic technologies can be deployed responsibly, equitably, and sustainably within global food systems.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this work.

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