Role of Genetically Modified Organisms in Agriculture Biotechnology and New Developments

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Abstract

Over the past 6 decades, GMOs have revolutionized agriculture through increasing crop yields and resistance to pests or diseases while boosting nutritional content. Through the discussion on genetic engineering techniques, this chapter highlights major molecular machinery (e.g., Agrobacterium-mediated transformation, biolistic and CRISPR/Cas9) that have made targeted improvement of traits possible. While these may come with some positives, GMOs also face their fair share of disadvantages (distrust from the public in regard to health aspects and environmental effects; poverty issues linked with bio-patented seeds as perhaps seen by smallholders). Advances made recently in gene editing technologies and regulatory frameworks are affecting the status of GMOS. In this chapter, we discus public engagement and open, candid conversations to dispel fears and improve trust in biotechnology. In conclusion, GMOs are an important means to tackle world agricultural problems yet the ongoing debate is necessary in order for them to be part of farming practices on a long-term basis. This chapter discusses the advantages, disadvantages, and most current developments of genetically modified organisms (GMOs) in agriculture.

Keywords: GMOs, Environmental effects, Health concerns, Public engagement, Molecular machinery, Nutritional content

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Introduction

Genetically modified organisms (GMOs) represent an advancement in agricultural biotechnology and offer innovative solutions to pressing global issues. These days with challenges, like climate change and a growing population making food production more challenging than ever before GMOs play a vital role in enhancing agricultural methods (Paniza, 2024). The Food and Agriculture Organization predicts that food production needs to rise by 70% by 2050 to meet the needs of 9 billion individuals globally (Simane et al., 2025). Utilizing methods alone would not suffice to achieve such a milestone; hence the integration of GMOs is crucial, in striving for a sustainable future (Gbashi et al., 2021). The enhancement of crop plants, through the incorporation of genes or the control of natural gene activity has played a crucial role in advancing crop development and agriculture as a whole. Genetic modification and the alteration of plants have enabled traits such as resistance to herbicides and insects' capacity to withstand stresses and disease resilience (Abobatta, 2020). Improved nutritional content in genetically engineered crops and 525 unique modified instances across 32 different crops have received approval for cultivation worldwide up, to now.

Transgenic technology adoption has been demonstrated to lower crop production costs, decrease the use of pesticides and insecticides, enhance crop yields, and lower CO_2 emissions (Hickey et al., 2019). However, there are obstacles to the broad use of transgenic crops with foreign DNA because of worries about possible human toxicity, allergies, and environmental hazards, such as the likelihood of gene flow, negative impacts on organisms that are not the intended target, development of resistance in insects and weeds, etc., (Karn et al., 2022). Alternative methods including cisgenesis, intragenesis, and most recently, genome editing, have been used as a result of these worries. Since some of these alternative technologies can be used to create agricultural plants devoid of foreign genes, it is anticipated that these crops will be more widely accepted by consumers and receive regulatory approvals more quickly than transgenic crops (Anzalone et al., 2019). For example, cultivated plants modified to resist pests can lessen reliance, on pesticides and promote sustainable farming methods while safeguarding beneficial insects as well (Montecillo et al., 2021). These modified crops encompass Bollgard cotton and StarLink corn that have been genetically altered to generate a protein derived from the Bacillus thuringiensis bacterium to eradicate the intended pests. These varieties have reduced pest damage very significantly, which means the yields are higher and fewer pesticides are used (Umesha et al., 2018).

Moreover, with the CRISPR-Cas9 technology, crop development has been revamped with the ability to deliver precise edits to plant genomes. This enables the development of crops that are not only highly productive but also resilient to changing climatic conditions. For example, scientists have been able to engineer different varieties of maize and rice that require minimal water intake but can still grow well in drier conditions; this is a basic adaptation in the face of increased global temperatures and changes in rainfall (Bortesi & Fischer, 2022). Besides high yields and tolerance, GMOs are a crucial way to address nutritional deficiencies globally. Biofortification of staple crops is one strategy that can boost the nutrient content of food. For instance, Golden Rice, engineered to contain more provitamin A (beta-carotene), seeks to eliminate vitamin A deficiency in developing countries, where rice is a mainstay diet staple. Projects in this regard indicate GMO's ability to positively influence health directly but, meanwhile improve food security.

Implementing GMOs poses notable economic effects. Studies say that farmers using GMO produce earn more due to saving on inputs and being able to produce more. GMOs have positively impacted the economies of regions such as South America, enhancing the livelihoods of farmers. Agricultural biotechnology in Brazil and Argentina has increased their agricultural exports and contributed to their national economies (Basso et al., 2024). GMOs are not adopted uniformly across the world. Most countries have embraced agricultural biotechnology, but some are still very cautious and have avoided it, fearing the effects of regulations and public perception. The European Union has strong regulations, requiring approval for crops before their commercialization in the market after long-term safety assessments. Such a regulatory approach reflects caution towards biotechnology (Beghin & Gustafson, 2021). A regulatory environment like this could discourage innovation and limit the benefits of GMOs where it is needed most in agricultural production.

The other factor that determines whether GMOs are accepted or not is public perception. Many consumers fear GMOs due to the misinformation as well as a lack of knowledge about genetic engineering (Thompson, 2023). A research study has shown that a good number of people lack scientific knowledge about GMOs thus creating a reason for fear over safety and environmental effects (Smith & Brown, 2024). This points to a need for general education programs that deliver the benefits and safety of GMOs in the creation of an informed discussion about biotechnology. There should be a focus on effective communication strategies that emphasize scientific consensus on the safety of GMOs and their ability to improve food security with reduced environmental impacts. Through public engagement through open dialogue, educational programs, and outreach initiatives, the gap between scientific communities and consumers will be bridged, with trust and understanding developed (Lee, 2022). GMO integration into sustainable farming methods will be a key focus in the future. Researchers are investigating how soil health, biodiversity, and carbon sequestration can all be enhanced by genetically modified crops (Kelley, 2023). For example, increased nutrient efficiency in genetically modified crops can lower fertilizer pollution, runoff, and environmental damage (Basso et al., 2024).

Innovations in agricultural biotechnology are also focused on crops that can grow well in marginal environments, thus not further stressing prime agricultural land. This approach supports food production and promotes conservation by saving natural habitats (Lisboa et al., 2024). Furthermore, the aspect that GMOs contribute in ameliorating climate change cannot be overlooked. A change in climate character leads to extreme weather cases happening frequently, and for a good crop to flourish with such challenges, resistance will be key. Developing crop resistance through agricultural biotechnology will be fundamental because further research and developments create a resilient crop towards an altering climate to safeguard its security for generations (Umesha et al., 2018). This chapter's goal is to examine how important genetically modified organisms (GMOs) are to solving the world's agricultural problems, especially in light of climate change and the growing demand for food production.

Understanding GMOs

GMO stands for genetically modified organism, and it refers to any plant, animal, or microorganism whose genetic material has been changed with biotechnology to give the desired characteristics. This usually involves taking out certain genes that affect the way an organism looks or interacts, but then replacing them with a healthier set of instructions. The history of GMO technology begins with the identification of DNA and how to work on genetic modification in plants by the late 20th Century (Gbashi et al, 2021).

Genetic Modification Strategies

Genetically Engineered Crops

The commercial introduction of genetically engineered (GE) crops occurred in the 1990s. Because of concerns about possible harm to the environment, human health, and ethical considerations, some individuals and organizations continue to oppose the technology even after it has been in production for 20 years. However, some worry that because of strict laws and less public money for the development of more beneficial products for society, technology is not realizing its full potential to enhance human health and the environment (Aggarwal et al., 2022). New developments in genetic engineering are complicating the ongoing discussion over these and other issues pertaining to the methods used in the first 20 years of genetic engineering. Genetically Engineered Crops expands upon earlier relevant Academies publications from 1987 to 2010 by looking back at the alleged benefits and drawbacks of GE crops and projecting what the future may hold for these developing genetic-engineering technologies. This research identifies areas of uncertainty regarding the effects of genetically engineered crops and food on the economy, agronomy, health, safety, or other factors, and it offers suggestions to close these gaps in safety evaluations, clarify regulations, and enhance GE technology access and innovation (Lubieniechi et al., 2025).

Agrobacterium

A strategy for introducing genes into crops called plant transformation based on agrobacterium-mediated transformation imitates the natural agrobacterium system. Numerous crop species have been successfully genetically transformed thus far by means of this technology, demonstrating an improvement or modification for one or more traits. Compared to other transformation techniques, this one offers a number of benefits, including cost-effectiveness and robust transgene integration (Javaid et al., 2022). Nevertheless, this method has numerous drawbacks, including low transformation efficiency, transgenic integration, off targets, and the majority of crops being resistant to agrobacterium. Therefore, in order to improve the genetic transformation efficiency of Agrobacterium-mediated transformation, it is imperative to investigate the main obstacles and potential fixes.

The hazards of Agrobacterium-mediated transformation in transgenic plants, the process used to create genetically modified crops using this technique, and the main crop species that have been successfully changed using it are all thoroughly examined. (Wen et al., 2022). The difficulties and issues surrounding Agrobacterium-mediated transformation are discussed and how they can be resolved in the future to enable successful genetic modification of crops through the use of cutting-edge biotechnology methods like CRISPR/Cas9 systems. The audience working on crop genome editing by Agrobacterium-mediated transformation will find great assistance in this review study, which also offers up numerous new avenues for future plant genetic transformation (Van Dijk, 2021).

Applications of CRISPR/Cas9 Genome Editing in Plant Species

Rice

The ability of CRISPR/Cas9 era to enhance the pleasant of agricultural goods is one in all its most extensive uses of in terms of sustainability. The first effective CRISPR/Cas9 manipulation of rice, a key food delivery for the arena's population (Fukagawa and Ziska, 2019), changed into achieved with the aid of (Miao et al., 2013), who showed that the approach will be applied for targeted changes in rice. Since this discovery, a variety of work has been finished to recognize the roles of unique genes and observe the results of gene modifications in rice with the intention of the use of the study’s findings in actual global applications. A work by using (Guo et al., 2020) that hired CRISPR/Cas9 to each overexpress and do away with the OsProDH gene in rice serves as an illustration of this. The OsProDH gene produces the mitochondrial enzyme proline dehydrogenase that is accountable for breaking down proline in rice. Proline is essential for protecting flora from a number of biotic and abiotic stresses as it triggers some physiological responses within the flowers and scavenges reactive oxygen species (ROS) (Li et al., 2022).

It was discovered that rice with an OsProDH gene mutation accumulated more proline, which helped to lower the levels of reactive oxygen species (ROS) (Guo et al., 2020). Therefore, rice may be given extended thermotolerance via editing the OsProDH gene and ultimately the metabolism of proline, rice might be given more thermotolerance. Therefore, rice might be given improved thermotolerance by way of enhancing the OsProDH gene and eventually the metabolism of proline (Guo et al., 2020).

Soybean

Other notable plant species have also benefited greatly from CRISPR/Cas9-based mutagenesis, which has yielded amazing mutation efficiency. Carried out the first CRISPR/Cas9 gene edited in soybeans by deleting the gene for the green fluorescent protein (GFP). This landmark finding prompted several efforts to use CRISPR/Cas9 gene editing in soybeans. Han et al., (2019) employed CRISPR/Cas 9 to cause a specific mutation in the E1 gene in order to regulate soybean flowering. They found that truncating the E1 protein accelerated the blooming period under long-day (LD) conditions, abolished the inhibition of the GmFT2a/5a gene, and boosted its expression. This alteration led to the creation of a photo-insensitive soybean variety, and it would be appropriate to introduce higher latitudes for soybeans shown in Figure 1 (Han et al., 2019).

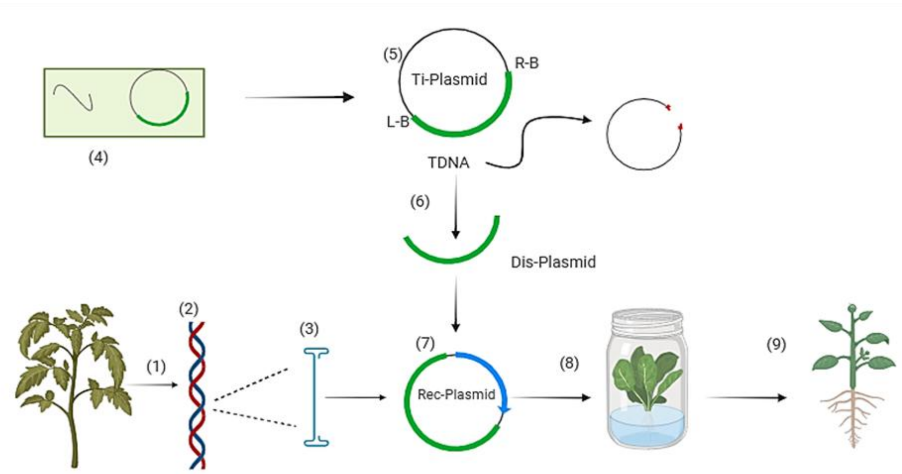

Fig. 1: Genetic modification in soybeans using Agrobacterium tumefaciens and Ti plasmid technology which is adapted to introduce desirable traits like herbicide resistance, pest resistance, or improved nutritional content (Retrieved from Bio Render).

Genetically Modified Crops

Through the use of biotechnology, genetically modified crops (GM crops) have been altered to exhibit particular desired characteristics, such as improved nutrition and resistance to pests and herbicides. Finding relevant genes, incorporating them into the plant's nuclear genome using Agrobacterium-mediated transformation and CRISPR/Cas9 procedures, and allowing the plants to regrow are some of the most crucial phases in the creation of genetically modified crops (Shehryar et al., 2020).

These crops increase the efficiency of agricultural practices as they require fewer chemicals, more specifically pesticides as demonstrated by BT cotton and golden rice. There are worries about the conservation of biodiversity, resistance management of pests, health of people consuming GM foods, and the political implications of GM agriculture including the need for stringent regulations. Overall, GM crops have proved to be a new technology in agriculture but have raised certain issues that concern the safety and risks of these crops for the environment and human health in the long run (Brookes & Barfoot, 2020).

Bacillus Thuringiensis Crops

Crops that are bacillus thuringiensis, like GMA corn or cotton, have been genetically engineered to express proteins derived from the bacterium Bacillus thuringiensis that kill specific insect pests. The technology has been extensively used in agriculture, especially in bacillus thuringiensis cotton and also the crops Bt corn because of their efficiency to manage key pest insects such as the cotton bollworm *(Helicoverpa zea*). Such crops, which help to reduce damage and improve production levels by reducing the use of chemical insecticides traditionally used (Brookes & Barfoot, 2018a).

One of the greatest advantages that also usually leads to direct economic and environmental benefits is reduced reliance on chemical insecticides which happened with terms Bt crops. Indeed, reductions in pesticide use with the adoption of Bt cotton have been shown to lower production costs for farmers while simultaneously diminishing environmental consequences related to chemical applications shown in Figure 2 (Pimentel, 2019). For example, Bt cotton can reduce the quantity of synthetic insecticides used and lower pesticide residues in the environment (Brookes & Barfoot, 2018b).

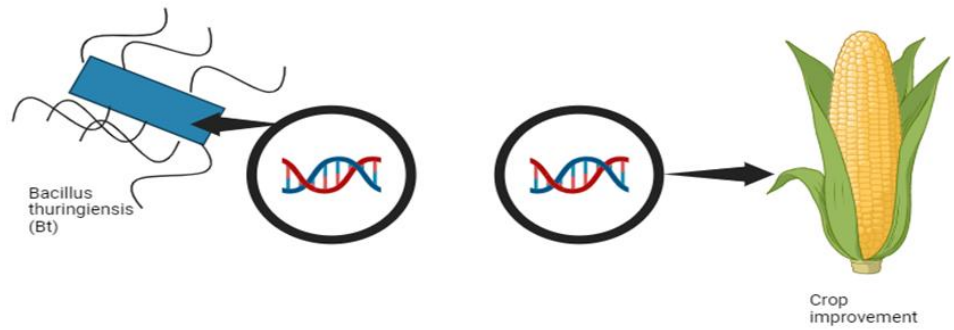

Fig. 2: The genetic modification process using Bacillus thuringiensis (Bt) to improve crops (Retrieved from Bio Render).

However, as with all insecticides, an alarm should sound whenever mechanisms of resistance to Bt crops are discovered. Over time, insect populations have been able to evolve resistance to the Bt proteins which can eventually render this technology ineffective. Integrated pest management strategies are essential as a solution from this risk. One of the major recommendations for refuge strategy and involves planting of non-Bt close to Bt. This also ensures that there are still some susceptible insect pests around so they do not develop resistance as easily or quickly to the Bt proteins (Nagaraj et al., 2024).

Golden Rice

Golden Rice is a genetically modified rice designed to combat vitamin A deficiency (VAD), a major public health problem affecting millions of people. Especially in developing countries. The gene responsible for the synthesis of beta-carotene comes from daffodils in genetically developed golden rice. The health of rice, is the staple food of millions of people. There is often a lack of essential nutrients in foods that rely on rice. Vitamin A is important for various physical functions, consisting of vision, immune reaction, and skin health. The World Health Organization has highlighted that VAD is a leading cause of preventable blindness in youngsters and extensively will increase morbidity and mortality from infectious sicknesses (World Health Organization, 2009).

Table 1: This table provides an overview of Golden Rice, a genetically modified crop designed to address vitamin A deficiency.

Aspect	Details	References
Purpose	Developed to prevent blindness in the young generation, a major health issue in growing countries.	(WHO, 2009)
Nutritional Impacts	Aims to increase morbidity from infectious sickness and to provide essential required vitamin A to people relies on rice as staple food.	(WHO, 2009)
Field Trials and Regulation	Regulatory our bodies in various nations have carefully assessed those trials to make certain protection for consumption and environmental impact.	(Smyth et al., 2020)
Public Perception	The debate about Golden Rice has underlined the necessity of transparency and public involvement in attempting to ease concerns regarding genetic modification.	(Yadav et al., 2024)
Current Advancements	The goal of recent developments has been to enhance Golden Rice's horticultural and agronomic performance by creating new, high-yielding, or disease-resistant cultivars.	(Zhang et al., 2023)

Golden Rice seeks to offer a sustainable answer by way of enhancing the nutritional intake of nutrition A amongst vulnerable populations. Since its inception, Golden Rice has gone through great discipline trials to assess its agronomic performance, protection, and efficacy. Regulatory While navigating a complex landscape sparked by public opinion and scientific data, our bodies in different countries have carefully evaluated those experiments to ensure protection for consumer and environmental impact (Smyth et al., 2020). Despite its potential advantages, Golden Rice has encountered strong criticism from anti-GMO activist groups. The Golden Rice controversy has highlighted the need for openness and public participation in efforts to allay worries about genetic engineering (Yadavet al., 2024). Proponents of Golden Rice, a staple in many nations, argue it is a powerful tool in the fight against starvation, while detractors maintain there are other, non-GMO crop alternatives for large-scale agriculture. With new high-yielding or disease-resistant cultivars, more recent advancements have attempted to enhance Golden Rice's horticultural and agronomic performance (Zhang et al., 2023). As more governments and organizations recognize the advantages of biofortified crops, efforts to integrate Golden Rice into regional food systems are beginning to bear fruit, propelled by both commercial and policy developments.

Biolistic Technique

The biolistic technique gives a novel solution to the mission of turning in DNA into dwelling cells and tissues. High-pace microprojectiles are employed to transport substances, which includes DNA, via membranes and cell partitions. The word "biolistics" refers to a sort of biological ballistics that is represented by way of the "shooting" of DNA into cells. Plant transformation the usage of biolistic techniques accommodates numerous steps which make contributions to its a hit final touch. In the first area, gold or tungsten debris are lined with the plasmid DNA constructs containing the target genes (Meyer et al., 2021). Subsequently, a gene gun is used to propel the aforementioned debris into plant.

This device propels the debris at an extreme speed with the use of both a jet of compressed air or small explosive materials (Gao et al., 2022). When particles are hurled at the goal plant tissue, they pass the cell wall and cellular membrane boundaries, as a result facilitating the doorway of DNA into the plant cells (Sheng et al., 2023). This allows the incorporation of recent talents with the altered DNA which could grow to be a part of the host plant's genetic records (Deng, 2024). Afterwards, such cells are implanted into the correct growth medium, so as to regenerate entire plants thru culturing techniques (Niu et al., 2021). This method has been applicable to many types of organisms, and so remains a critical component of plant agricultural technology.

The biolistic process has a number of basic advantages over other methods of plant transformation shown in Figure 3. Regardless of the species or type of tissue, the biolistic approach seems to work well, is quick and easy to use, and should make it easier to directly alter totipotent tissues like pollen, embryos, meristems, and morphogenic cell cultures. Furthermore, it seems that organelle transition is a unique application for the biolistic process. The biolistic process has two drawbacks: it's still in its early phases of development and needs specialized equipment. As a result, delivery efficiencies remain below those possible in highly optimized transformation methods such tobacco agrobacterial infection or electroporation. Additionally, prospective users should be ready to invest some effort in customizing current procedures to their particular species or target tissue (Bate et al., 2021).

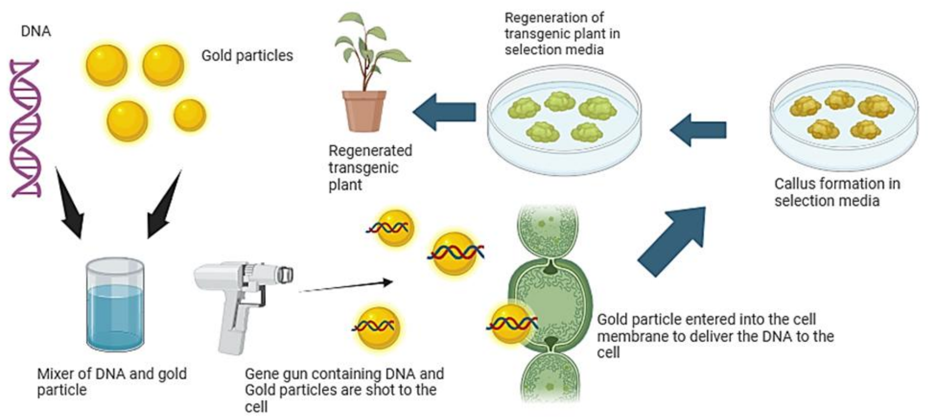

Fig. 3: The schematic diagram shows the method of genetic transformation of the plant. It illustrates the bombardment of gold particles carrying the gene of interest onto cultured plant cells to regenerate transgenic plants (Retrieved from Bio Render)

Public Perception and Ethical Consideration

The public discourse on genetically modified organisms (GMOs) in agriculture is dominated by opposing viewpoints on their dangers and advantages. Their religious ministry has, however, somewhat influenced support for bio-resources. They argue that in this world where individuals are protected, eradication of hunger, control of malnutrition, alleviation of diseases, and enhancement of health and quality of human life are possible for everyone. Emerging technologies, however, have not received universal acceptance. Some insist that we cannot help humanity without endangering public health and cultural ecology. Others are just opposed to that research for religious and ethical reasons. Mixing of gene from different species is regarded by some as “playing God” or violating the “Natural Order” (Lala, 2020).

Biosafety of (GM) crops is an emerging field which encompasses scientific inquiries, ethical concerns as well as policy and regulatory strategies aimed at evaluating and controlling risks of harm to humans or animals such as food and animal feed concerns as well as to the environment from the use of modern biotechnology products (Ewa et al., 2022). Bio-policy refers to the rules, norms, and ethical considerations that govern the development, production, and use of biotechnology products. This encompasses social and political mechanisms that help shape and administer national and international policies on biotechnology. A primary focus in this framework is the Trade-Related Aspects of Intellectual Property Rights (TRIPS) Agreement, which is a fundamental legal instrument for harmonizing international standards for the protection of intellectual property rights. Every country that is a member of the World Trade Organization (WTO), which deals especially with international trade of agricultural products, must implement a patent system in all members and the TRIPS Agreement also cuts across modern biotechnology. Patent systems are made to advance inventions by way of monopolizing the innovations for a limited time.

Conclusion

To sum up, GMOs are a necessary step forward in agricultural biotechnologies that have the capacity to increase crop productivity, its toughness and even nutrition value. However, there are still some problems concerning health, environmental and ethical aspects that the public has. This calls for an open and active informed dialogue. Recent updated information including the very latest tools such as gene editing applications especially CRISPR/Cas9 clearly indicate that there is more to GMO technology than meets the eye. As we define these issues, building confidence and comprehension over biotechnology will be fundamental in the encouragement of the use of GMOs in the current agricultural practices as a way of food security and nutrition’s problem. Other than that, looking into the problem objectively as opposed to one sided belief of who is right or wrong avoids imbalances in GMO implementation.

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