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Understanding Genetically Modified Crops (GMOs): Benefits, Risks, and Future Prospects

Muhammad Ahtisham and Zainab Obaid

ABSTRACT

Genetically modified (GM) crops have revolutionized the agricultural sector by allowing scientists to rapidly introduce novel genes for desirable traits such as herbicide tolerance, pest resistance, bio-fortification, and disease resistance from one species to another, which are becoming difficult to achieve using conventional breeding methods. GM crops have improved the overall productivity of many crops, contributing positively to food security. In the past few decades, GM crops have shown significant positive effects, especially effective weed and pest management. Because of this success, GM crops in the past few decades have expanded up to 2.15 billion hectares globally. Despite these benefits, there are some serious potential issues associated with GMOs that have to be addressed such as weeds becoming resistant to herbicides due to their extensive use in GM crops, the potential threat of insects becoming resistant to CRY protein released by *Bacillus thuringiensis* (BT) crops, and the issues of biosafety and biodiversity of other plant and animal species linked with GM crops directly or indirectly. The review explores the basic techniques used to develop GM crops and explains the benefits of GMO crops in the field of agriculture, especially in weed management, disease resistance, and bio-fortification. And also, it highlights the prospects and examines the risks associated with GMO crops.

Keywords: GM crops, Herbicide tolerance, Pest resistance, Bio-fortification, Gene transfer techniques

Introduction

For decades, scientists have been using conventional breeding methods for genetic improvement in crops, and these methods have proven to be effective but are still comparatively very slow in contrast to modern biotechnological tools of crop improvement, such as the transformation of a desirable gene from one species to another.¹ In genetically modified (GM) crops, the genome of the plants is modified by inserting a novel gene of interest from one species to another using *Agrobacterium*-mediated gene transfer techniques or directly through direct gene transfer techniques, and the resulting plants are called transgenic plants.² These innovations have helped to overcome the challenges of food security, especially in areas where agricultural productivity is constrained.³ It is evident that the initial year of commercialization of GM crops has resulted in substantial agronomic, health, and environmental benefits to farmers, and these benefits have been utilized by both large and small farmers, consequently increasing the cultivation of GM crops to 2.15 billion hectares in only 21 years.⁴

Nevertheless, it remains a concern that just as developing countries are likely to get more benefits from these technologies so do they are likely to be affected in an adverse manner.⁵ Moreover, due to the concerns related to the adverse effects of GM crops such as antibiotic resistance, toxicity, and allergen city GM crops have not been accepted widely.⁶

Despite all these ethical concerns, GM crops have shown a substantial increase in the area of production. Thus, adoption of GM crops has increasingly become the fastest adapted modern agriculture crop improvement technique as only in 2017, 17 million farmers in 26 countries planted GM crops with an estimated market value of US\$ 18.2 billion. In GM crops, the major traits of commercial interest are herbicide tolerance, biotic and abiotic resistance, and bio-fortification.⁴ Thus, a proper understanding of GM crops is crucial for developing sustainable solutions for the environmental challenges faced by the agricultural sector while ensuring public safety and trust.⁷

In this review, we cover the scientific advancements in GM crops and evaluate the potential benefits, risks regulatory measures, and prospects of GM crops.

Understanding GMOs

The development of GM crops has gone through several transitions since their inception and with the incorporation of new and more precise gene editing tools to introduce more favorable traits in crops. Most of the techniques such as DNA-editing techniques are linked with a direct manipulation of the gene action. Various gene transformation technologies are available to develop GM crops, but the most common ones are biolistic gene transfer (gene gun method) and *Agrobacterium*-mediated gene transfer.⁸

Agrobacterium-Mediated Gene Transfer

Agrobacterium-mediated gene transfer is a commonly used technique to naturally transfer a gene from one species to another to develop GM crops.⁸ *Agrobacterium tumefaciens* is a soil-borne bacterium with the ability of transferring its portion of DNA into the host plant, resulting in the formation of galls on the affected part of the plant. Scientists have replaced this gall-causing gene with a gene of interest like a pest resistance gene and used the modified bacteria to transform the gene of interest in plants. Once the gene is transferred, the transformed cells are cultured to produce GM plants with the gene of interest, and much research has been done to improve the editing machinery of the *Agrobacterium* to make it more efficient for editing the genome

of plants.⁹ A precise understanding of how the *Agrobacterium* interacts with the cell factors and processes of the host offers a broader use of this technique in developing GM crops (Figure 1).⁹

Gene Gun Method (Biolistic)

It is also called as particle bombardment approach to transfer genes and was first developed in 1980. This technique involves the transfer of DNA into the targeted plant tissue by using gold or tungsten particles of 0.5 μ m in size. In this method, the leaf tissue of the plant after placing on the selective medium is bombarded with 0.5 μ m, metal projectile particles using compressed helium, and the particles pass throughout the plant cell and enter the nucleus under favorable condition, transferring the gene of interest in the plant.⁸ This method is helpful for the transformation of crop species that were previously difficult to

transform, such as maize, wheat, and barley. However, this method has drawbacks such as tissue damage and low efficiency of transformation (Figure 2).⁸

GMOs and Their Benefits

GM crops are becoming a modern solution to the modern problems in the agricultural sector with proven practical examples of crop improvement.¹⁰ This portion of the review highlights the magnitude of the benefits of GM crops in the commercial agricultural sector for crop improvement in traits of agronomic importance.

Herbicide-Tolerant Crops

Weeds affect the overall productivity of crops to a great extent with losses of US\$ 11 billion in only 10 crops only in India and the losses reached up to 35.8% in soybeans, 18.6% in wheat, and 13% in rice. Herbicide-resistant GMO crops cover almost 80% of the

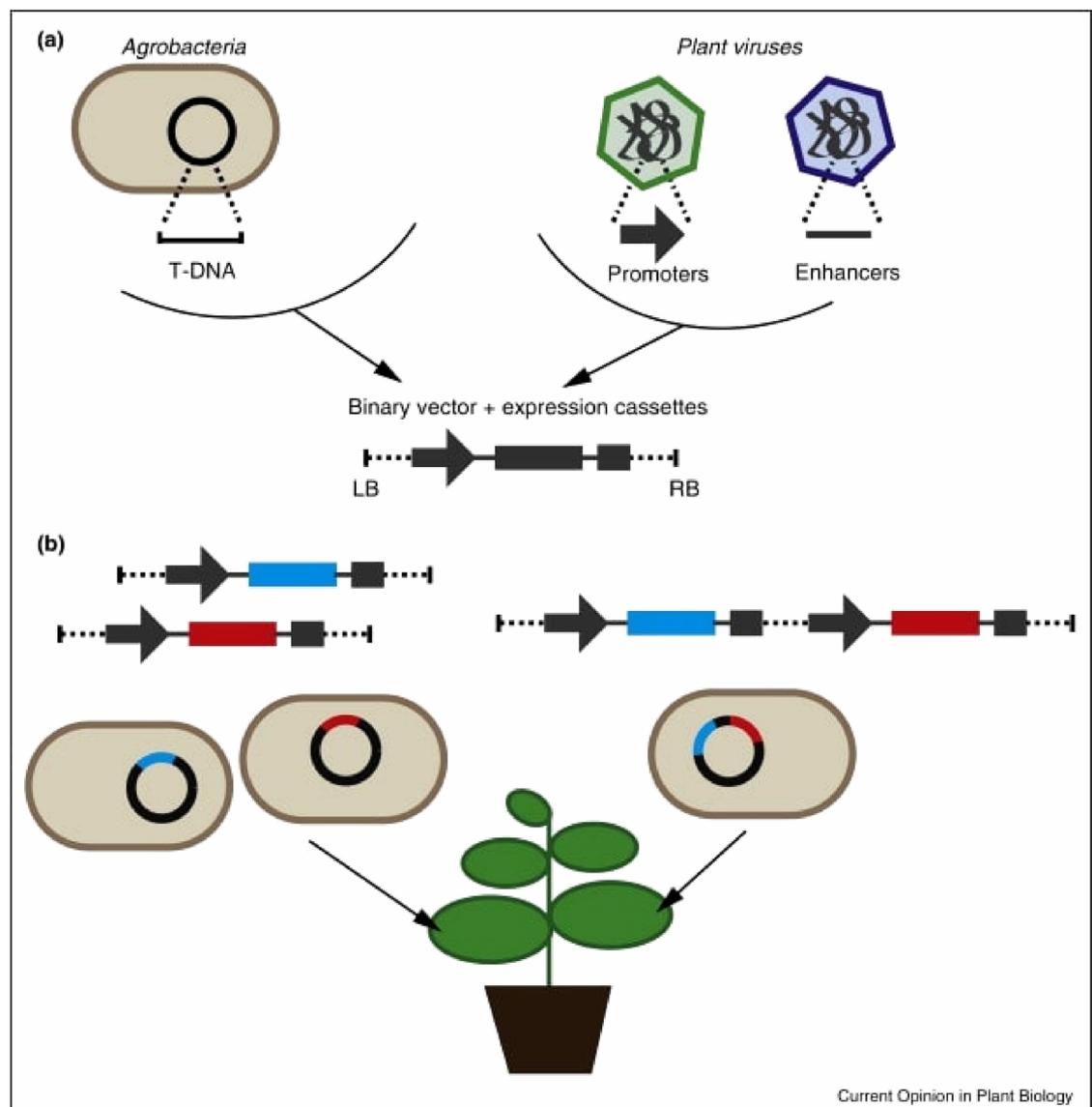


Fig 1 | Functional diagram of *Agrobacterium*-mediated gene transfer aided by a plant virus

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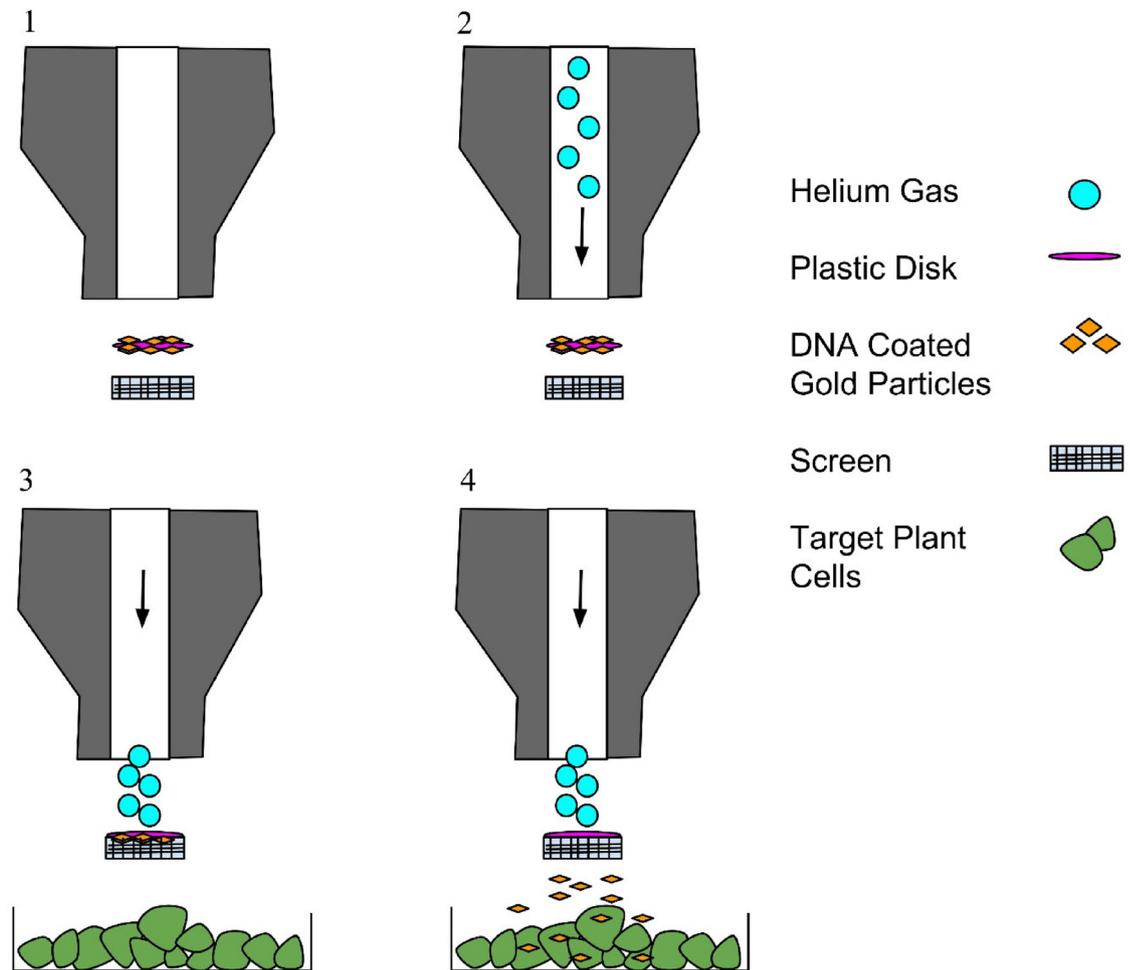


Fig 2 | Components of gene gun and mechanism of its functioning

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total area of all GMO crops all over the world.¹¹ Since 1996, weedicide-resistant crops, especially glyphosate-resistant GM crops such as corn, soybeans, and cotton, have revolutionized weed management with reliance on glyphosate only to manage weeds. With advancements in technology, new crops with a broader range of resistance to multiple weedicides, weed management will become more efficient and will ensure high productivity in agriculture.¹ In many crops such as corn, soybeans, cotton, canola, rice, and sugar beet, Glyphosate-Resistant (GR) has been introduced with the transformation of genes, such as *zm-2mepsps*, *ocp4epsps*, *cp4epsps*, *cp4epsps*, *cp4epsps*, *goxv247*, *bar*, and *cp4epsps*, respectively.¹ The commercial release of Roundup Ready (RR) soybean in 1996 revolutionized the history of weed management, and today about 80% of the area of soybeans is covered by RR soybean.¹² RR soybean was developed by Monsanto in 1996 by engineering the soybean to have the gene from the soil bacterium *Agrobacterium tumefaciens* which made the soybean tolerant to broad-spectrum herbicides. The Roundup (glyphosate) in RR soybean helps farmers control the weed by a simple foliar application of glyphosate over the crops, and it covers about 60% of the acreage of soybeans all over the world.¹³

Adaptation of the farming community has been very rapid for glyphosate-resistant (GR) crops. Currently, about 90% of the soybean area is cultivated by GR soybeans in the USA and in Argentina, out of the total area of production of soybeans, within just four years of its introduction, GR soybeans have been cultivated on 90% of the area.¹¹ By reducing the need for multiple weedicides for weed management in crops, GR crops help in soil conservation through sustainable management of weeds.¹⁴

Pest Resistance in Crops

The annual losses of arthropods (insects) pests may affect up to 20% of crop productivity, leading to estimated losses of US\$ 470 billion.¹⁵ GM crops producing insecticidal protein from genes transformed from the bacterium *Bacillus thuringiensis* (BT) have revolutionized the field of pest management in agriculture. BT has played a significant role in reducing the need for foliar application of pesticides by equipping plants with the ability to produce their insecticidal toxin. Due to these insecticidal properties, BT toxin-engineered crops covered 11.4 million ha only in 2000.¹⁶ BT cotton has helped many farmers in India, China, and the USA to control bookworms by reducing the use of

insecticides, making it more environmental friendly and cost-effective.^{17,18} BT cotton has improved the crop yield by reducing pest pressure.¹⁶ Due to the suppression of the pest, yield improvement has been observed in both BT and non-BT fields in the USA.¹⁷ Many varieties of maize, cotton, and, in some cases, potatoes are registered as BT varieties commercially. Based upon the data collected, these crops have shown a positive effect on the crop yield and the grower as well by reducing the cost of insecticides.¹⁶ From all these facts, it is evident that BT crops have played a positive economic and social role by reducing the overall risk and need for synthetic insecticides.¹⁸

Bio-Fortified Crops

Bio-fortification is a broad term used for enhancing the nutritional profile of crops.¹⁹ About 2 billion people all over the world are suffering from malnourishment and 820 million from hunger.²⁰ Bio-fortified crops are a great solution to tackle malnutrition, especially in developing countries as the bio-fortification of staple crops such as bio-fortified cassava and potatoes with vitamin A can help consumers overcome the deficiency of nutrients.²¹ Only the deficiency of vitamin A have resulted in 4500 deaths all over the world, and golden rice bio-fortified with vitamin A due to the transformation event GR2E can be a cost-effective solution to overcome the deficiency of vitamin A in populations where rice is used as a staple crop. These biofortified crops are also recommended by the WHO, with golden rice as an example.²² Golden rice was developed by using the β -carotene biosynthetic pathway in the rice endosperm, and it was achieved by transforming lycopene β -cyclase and phytoene synthase genes from *Erwinia uredovora* and with this modification, β -carotene production in the rice endosperm became a success.²³ To enhance the nutritional profile of maize, GM maize was developed by reducing zein proteins (19- and 22-kD α -zeins), hence enhancing the balance of free amino acids.²⁴ GMO bio-fortified plants have great potential for solving the problem of malnutrition all over the world by utilizing the limited land resources.¹⁹ Although not many bio-fortified GMOs are present, still they can offer a great solution to the problem of malnutrition in the future.

Disease Resistance

Biotic stressors such as viruses, bacteria, and fungi are causing severe yield losses all over the world and are burdening the demand for food for the ever-growing human populations, and these losses are mostly caused by diseases, pests, climate changes, and loss of arable land.²⁵ Plant viruses are a real threat to global food security and with the present situation of conventional breeding failing to produce disease-resistant plants, genetic engineering offers a fast alternative for making plants resistant to viruses. Despite the skepticism of the public, these GM crops are safe and benefit food security.²⁶ Rainbow papaya was the first GMO fruit crop and was developed against papaya ring spot virus (PRSV). It was developed by incorporating the DNA of

the virus into the papaya plant, and it was found that both GMO and non-GMO papaya plants had the same level of benzyl isothiocyanate (BITC) and had no alleviated level of any allergens.²⁷ In another study, five transgenic squash lines were developed expressing a coat protein from zucchini, cucumber, and watermelon mosaic virus. It was found that the CZW-3 line showed the highest level of resistance with no synthetic infection and also showed a 50% increase in market-able yield.²⁸ At Wageningen University, research conducted from 2006 to 2015 worked on the transformation of Durable Resistance in potato against *Phytophthora* (DuRPh) using *Agrobacterium*-mediated transformation from wild species into the local cultivar successfully reduced the use of fungicides by up to 80%.²⁴

Future Prospects

As the global population is estimated to reach up to 9 billion by 2050, food security and agricultural sustainability are at greater risk due to the increasing food demands, and GMOs offer a promising solution.²⁹ The current food production needs a significant rise of up to 40% to meet future nutritional needs, and GM crops give us some hope with their innovative results.³⁰ GMOs have already increased yields by 22% and reduced the use of pesticides by 37%, leading to enhanced environmental and economic safety.³¹ GM crop adoption by farmers across different countries has also shown better economic gains for farmers, contributing to rural development.³² Increased productivity levels of GMO crops during the recent years are helping to reduce farmland expansion.³³ It is well known that farmland expansion is one of the most important contributing factors to biodiversity loss and climate change.²⁰ Bio-fortified GMOs have great potential to tackle malnutrition worldwide, as they have shown promising results in this area.²⁰

Although there is an increasing trend of GMO crops all over the world, the scientific, political, ethical, religious, and environmental aspects of GMOs should be addressed in the future.³⁴ Although GM crop technology has emerged, several issues could hinder its widespread acceptance, and alternative technologies such as cisgenesis and genome editing tools can address the issues and can ease the process of development of GM crop varieties, and it is expected that crop varieties developed using these technologies can have higher consumer acceptance rate and can get fast regulatory approvals.⁶

Many EU member states can oppose the agrobiotechnology policy in the future, resulting in more complex and multi-level policies, but still, the EU member states are not as coherent as they should be in policies regarding GM crops.³⁵

Risks Associated with GMOs

Although GM crops offer several benefits, they also present potential risks that are associated with their use, such as herbicide-tolerant, pest-resistant, bio-fortified, and disease-resistant crops, although the introduction of any GMO in the market is always

governed by science-based risk assessment and management.³⁶ Many researchers are showing their concerns about the potential adverse effects of GMOs on human health and overall environmental sustainability.³⁷

GM herbicide-tolerant (GMHT) crops initially associated with low use of herbicides can lead to herbicide resistance in weeds due to repeated use of the same herbicide, and this repeated use of herbicides has led to a gradual increase in reliance on herbicides, resulting in a harmful impact on the environment and a rise in the production cost of farmers.³⁸ With such a strong defense system, GM plants can become a weed by interrupting the growth of the other plant species in the surroundings, hence disturbing the biodiversity in the ecosystem.³⁹ A significant impact of weeds has been observed in both GMHT and conventional varieties as lower biomass was observed in GMHT treatments and in the case of maize weed population increased, leading to varying effects of GMHT management on weeds.⁴⁰

Although the use of BT crops has revolutionized pest management, still it has adverse effects. The CRY protein produced by BT crops significantly affects the soil ecosystem. Additionally, the BT crops can alter the overall soil respiration and protein persistence, affecting the biodiversity from the ecosystem below the ground.⁴¹ GM BT crops can produce CRY protein despite the concerns of the rapid development of resistance in insects. It has not been reported significantly yet, but still relative importance of the facts depends upon different regions and pests. The success of BT crops has exceeded expectations, but still they do not get away with the problem of pests becoming resistant to CRY protein in the future.⁴²

GMO plants are a new plant variety and they can have adverse effects as well which have not been discovered, and these concerns are becoming more vital questions to answer while developing GMOs. Moreover, the introduction of a new gene in a plant can lead to the production of new allergens.⁴³

Conclusion

The future problem of food security needs novel solutions, and GM crops are one of them with their proven impact in agriculture. GM crops hold a bright future for humans if proper regulatory measures are considered during development and commercialization.

References

- 1 Green JM. The benefits of herbicide-resistant crops. *Pest Manage Sci.* 2012;68(10):1323–31.
- 2 Griffiths A, Wessler S, Lewontin R, Gelbart W, Suzuki D, Miller J. *Introduction to Genetic Analysis.* 8th ed. FreemanWH. 2005.
- 3 Qaim M. Benefits of genetically modified crops for the poor: household income, nutrition, and health. *New Biotechnol.* 2010;27(5):552–7.
- 4 Briefs I. Global status of commercialized biotech/GM crops in 2017: Biotech crop adoption surges as economic benefits accumulate in 22 years. *ISAAA brief.* 2017;53:25–6.
- 5 Ricoch AE, Guillaume-Hofnung M, Kuntz M. *The Ethical Concerns About Transgenic Crops.* Portland Press Ltd. 2018. pp. 803–11.
- 6 Kumar K, Gambhir G, Dass A, Tripathi AK, Singh A, Jha AK, et al. Genetically modified crops: Current status and future prospects. *Planta.* 2020;251(4):91.

- 7 Bridi RM. *The Political-Economy of Science and (Bio) Technology: The Emergence of Agricultural Biotechnology in Canada.* 2016. Available from: <https://core.ac.uk/download/pdf/84743885.pdf>
- 8 Mubeen H, Naqvi RZ, Masood A, Shoaib MW, Raza S. Gene transformation: methods, uses and applications. *J Pharmaceut Biol Sci.* 2016;4(2):54.
- 9 Tzfira T, Citovsky V. Agrobacterium-mediated genetic transformation of plants: biology and biotechnology. *Curr Opin Biotechnol.* 2006;17(2):147–54.
- 10 Raman R. The impact of Genetically Modified (GM) crops in modern agriculture: a review. *GM Crop Food.* 2017;8(4):195–208.
- 11 Duke SO, Powles SB. Glyphosate-resistant crops and weeds: Now and in the future. *AgBioForum.* 2009;12:346–57.
- 12 Dill GM. Glyphosate-resistant crops: history, status and future. *Pest Manage Sci.* 2005;61(3):219–24.
- 13 Konduru S, Kruse J, Kalaitzandonakes N. *The Global Economic Impacts of Roundup Ready Soybeans. Genetics and Genomics of Soybean:* Springer. 2008. pp. 375–95.
- 14 Green JM. Evolution of glyphosate-resistant crop technology. *Weed Sci.* 2009;57(1):108–17.
- 15 Sharma S, Kooner R, Arora R. Insect pests and crop losses. In Arora R, Sandhu S (eds) *Breeding Insect Resistant Crops for Sustainable Agriculture 2017*(pp. 45–66). Springer.
- 16 Shelton AM, Zhao J-Z, Roush RT. Economic, ecological, food safety, and social consequences of the deployment of Bt transgenic plants. *Annual Rev Entomol.* 2002;47(1):845–81.
- 17 Hutchison WD, Burkness EC, Mitchell PD, Moon RD, Leslie TW, Fleischer SJ. Areawide suppression of European Corn Borer with Bt Maize reaps savings to non-Bt maize growers. *Science.* 2010;330:222–5.
- 18 Qaim M, Zilberman D. Yield effects of genetically modified crops in developing countries. *Science.* 2003;299(5608):900–2.
- 19 Hirschi KD. Genetically modified plants: nutritious, sustainable, yet underrated. *J Nutrition.* 2020;150(10):2628–34.
- 20 Boliko MC. FAO and the situation of food security and nutrition in the world. *J Nutrition Sci Vitaminol.* 2019;65(Supplement):S4–8.
- 21 Ilona P, Bouis H, Palenberg M, Moursi M, Oparinde A. Vitamin A cassava in Nigeria: crop development and delivery. *Afr J Food Agri Nutrition Develop.* 2017;17(2):12000–25.
- 22 Dubock A. An overview of agriculture, nutrition and fortification, supplementation and biofortification: Golden Rice as an example for enhancing micronutrient intake. *Agri Food Sec.* 2017;6(1):59.
- 23 Beyer P, Al-Babili S, Ye X, Lucca P, Schaub P, Welsch R, et al. Golden rice: Introducing the β -carotene biosynthesis pathway into rice endosperm by genetic engineering to defeat vitamin A deficiency. *J Nutrition.* 2002;132(3):506S–10S.
- 24 Haverkort A, Boonekamp P, Hutten R, Jacobsen E, Lotz L, Kessel G, et al. Durable late blight resistance in potato through dynamic varieties obtained by cisgenesis: Scientific and societal advances in the DuRPh project. *Potato Res.* 2016;59:35–66.
- 25 Junaid M, Gokce A. Global agricultural losses and their causes. *Bull Biologic Allied Sci Res.* 2024;2024(1):66.
- 26 Niraula PM, Fondong VN. Development and adoption of genetically engineered plants for virus resistance: advances, opportunities and challenges. *Plants.* 2021;10(11):2339.
- 27 Kaushal N, Sood N, Kaur M, Singh T. *Rainbow papaya. Genetically Modified Crops and Food Security:* Routledge. 2022. pp. 151–61.
- 28 Fuchs M, Tricoli DM, Carney KJ, Schesser M, McFerson JR, Gonsalves D. Comparative virus resistance and fruit yield of transgenic squash with single and multiple coat protein genes. *Plant Disease.* 1998;82(12):1350–6.
- 29 O'Sullivan JN. Demographic delusions: World population growth is exceeding most projections and jeopardising scenarios for sustainable futures. *World.* 2023;4(3):545–68.
- 30 Qaim M, Kouser S. Genetically modified crops and food security. *PLoS one.* 2013;8(6):e64879.
- 31 Klümper W, Qaim M. A meta-analysis of the impacts of genetically modified crops. *PLoS one.* 2014;9(11):e111629.
- 32 Brief I. Global status of commercialized biotech/GM crops: 2016. *ISAAA Br.* 2015(54):3–13.
- 33 Qaim M. Globalisation of agrifood systems and sustainable nutrition. *Proc Nutr Soc.* 2017;76(1):12–21.
- 34 Bellia C, Pilato M. Actuality and future prospects on GMOS crops in agriculture. Some main aspects and problems. *Qual Access Success.* 2011;12:280–8.

- 35 Tosun J, Shikano S. GMO-free regions in Europe: an analysis of diffusion patterns. *J Risk Res.* 2016;19(6):743–59.
- 36 Craig W, Tepfer M, Degrassi G, Ripandelli D. An overview of general features of risk assessments of genetically modified crops. *Euphytica.* 2008;164:853–80.
- 37 Gurian-Sherman D. Failure to Yield: Evaluating the Performance of Genetically Engineered Crops. Union of Concerned Scientists. 2009.
- 38 Bonny S. Genetically modified herbicide-tolerant crops, weeds, and herbicides: overview and impact. *Environ Manage.* 2016;57(1):31–48.
- 39 Fontes EM, Pires CS, Sujii ER, Panizzi AR. The environmental effects of genetically modified crops resistant to insects. *Neotropic Entomol.* 2002;31:497–513.
- 40 Nervous AAFri, Diseases M, Heard M, Hawes C, Champion G, Clark S, et al. Weeds in fields with contrasting conventional and genetically modified herbicide-tolerant crops. II. Effects on individual species. *Philos Trans Royal Soc London Series B: Biol. Sci.* 2003;358(1439):1833–46.
- 41 Icoz I, Stotzky G. Fate and effects of insect-resistant Bt crops in soil ecosystems. *Soil Biol Biochem.* 2008;40(3):559–86.
- 42 Tabashnik BE, Carrière Y, Dennehy TJ, Morin S, Sisterson MS, Roush RT, et al. Insect resistance to transgenic Bt crops: lessons from the laboratory and field. *J Econ Entomol.* 2003;96(4):1031–8.
- 43 Papparini A, Romano-Spica V. Public health issues related with the consumption of food obtained from genetically modified organisms. *Biotechnol. Annu. Rev.* 2004;10:85–122.