Benefits of Agricultural Biotechnology

Subjects: Plant Sciences | Agriculture, Dairy & Animal Science
Contributor: Boon Chin Tan, Mohd Fadhli Hamdan, Siti Nurfadhlina Mohd Noor

As agricultural production approaches a bottleneck due to limited arable lands, extreme weather, and increasing food demand, novel tools are needed to produce more resilient, efficient, and high-yielding crops to ensure global food security. Modern biotechnology tools with improved specificity and efficiency could eventually become the main driver of agricultural improvement, overcoming the limitations of conventional practices in improving crops.

Keywords: biotechnology ; breeding ; crop improvement ; genetically modified crops ; agriculture ; plant science

1. Improved Crop Yield and Efficient Land Use

In the Green Revolution era, the widespread utilization of fertilizers and pesticides has significantly boosted agricultural production. Unfortunately, their usage as agricultural inputs has been reported to be a limiting factor towards the end of the Green Revolution era as the global yield has begun to plateau for some major cereal crops [1]. A prominent benefit of genetic modification (GM) technology is its ability to increase crop yield within the same cultivation area with fewer inputs, mitigating the shrinking size of arable lands available for crop cultivation. According to the Food and Agriculture Organization (FAO), the arable land for food production per person will decrease from 0.24 ha in 2014 to only 0.18 ha in 2050. This does not include the additional usage of land to produce biofuel feedstock or the effects of urbanization or soil degradation [2]. Thus, there is a compelling need to produce higher agricultural yields by adopting GM technology to increase the food supply.

The main impact of GM technology on improving crop yields has been through better weed control and reducing the damage caused by pests through the cultivation of herbicide-tolerant and insect-resistant crops. As a result, from 1996 to 2018, the application of GM technology has increased the global production of the main crops by producing an additional 498 million tons of corn, 278 million tons of soybean, 32.6 million tons of cotton lint, and 14.1 million tons of canola [3]. Without the cultivation of GM crops during this period, additional arable land of 12.3 million ha of soybeans, 8.1 million ha of corn, 3.1 million ha of cotton, and 0.7 million ha of canola would have been needed to cultivate the conventional crop equivalent [3]. This would have required the clearance of more areas from the tropical forests for cultivation and the use of more fertilizers, herbicides, and pesticides, as well as irrigation, to gain the same reported yield. The increase in crop yield is supported by a meta-analysis of 147 original studies from 1996 to 2014, which reported that GM technology had increased crop yields by 22%, with the yield gains larger for insect-resistant crops than for herbicide-tolerant crops [4].

Another interesting meta-analysis of data from 130 publications found that gene overexpression, or the ectopic expression of transporter genes or other gene types, in three major GM cereals (rice, wheat, and corn) had significantly increased the overall grain yield by 16.7% on average [5]. Studies on these GM crops have mainly focused on genes with probable essential roles in improving the nitrogen uptake efficiency of crops. One example is the overexpression of alanine aminotransferase (*AlaAT*) genes, which are responsible for the increase in nitrogen utilization efficiency (NUtE; the biomass or grain yield per unit of nitrogen uptake) in canola and rice [6][7]. Li et al. [5] further suggested that the increased yield in the GM crops might depend on the higher shoot biomass, nitrogen uptake efficiency (NUpE; plant roots capacity to acquire nitrogen from the soil), and partial factor productivity of nitrogen (PFPN; grain yield per unit of nitrogen applied in soil). In another meta-analysis study on peer-reviewed literature (from 1996 to 2016) on GM corn, the study found strong evidence of higher grain yield, ranging from 5.6 to 24.5%, higher than for the true non-GE or near-isogenic line [8]. The GM lines also contained lower concentrations of mycotoxins (~28.8%), fumonisin (~30.6%), and thricotecens (~36.5%) [8]. The evidence clearly shows the benefits of GM technology in improving crop yield and reducing the accumulation of harmful toxins in the grain.

2. Economic Benefits to Farmers and Consumers

Through better management of weeds and pests and reduction in cost production, GM technology has significantly benefited farmers, with an additional gross income of USD 225.1 billion for the period 1996–2018 [3]. In 2018, most of the income benefits were earned by farmers in developing countries, where they received 53.7% of total income benefits, with an average of USD 4.41 received for each extra dollar invested in GM crop seeds [3]. This is consistent with previous studies showing that biotechnology applications in agriculture have brought economic benefits to numerous small-scale landholders in developing countries [9][10]. Moreover, GM technology not only benefits farmers and agribusinesses, but also consumers through lower costs of food supplies. It is conceivable that without the adoption of agricultural biotechnology that helped boost food supplies, commodity prices would have risen [11].

3. Reduced Environmental Impacts of Agriculture

The adoption of biotechnology in agriculture from 1996 to 2018 has lessened agriculture's environmental impact by reducing pesticide spraying by 775 million kg, representing a global reduction of 8.3% [12]. A meta-analysis demonstrated an overall reduction in chemical pesticide use by 37% from 1996 to 2014 due to biotechnology adoption [4]. The shift from conventional tillage (CT) to reduced tillage or no-tillage (RT/NT) farming systems in the cultivation of GM crops has resulted in a further reduction in fuel use by 12,799 million liters which have led to a significant reduction in global greenhouse gas (GHG) emissions of 34,172 million kg of carbon dioxide. Consequently, soil quality was enhanced by the retention of about 302,364 million kg of carbon dioxide [12].

4. Increased Tolerance to Crop Diseases

The global crop yield loss due to emerging and re-emerging pests and diseases is relatively high and was estimated to be 21.5%, 30%, 22.5%, 17.2%, and 21.4% for wheat, rice, corn, potato, and soybean, respectively [13]. The food-deficit regions of the Indo-Gangetic Plain and sub-Saharan Africa are reported to have suffered the highest crop losses [13]. Since the development of virus-resistant tobacco expressing the tobacco mosaic virus (TMV) coat protein [14], various biotechnological strategies have been applied to confer disease resistance in crops. These strategies include intervention in pathogen recognition/perception, pathogen effector binding, altering the expression of genes in plant defense signaling, targeting recessive resistance traits/susceptibility genes, interspecies transfer of dominant plant resistance genes, and utilization of antimicrobial peptides and RNAi [15]. One of the most successful stories of biotechnological application in crops to mitigate virus infection is the papaya ringspot virus (PRSV)-resistant papaya, which can resist PRSV infection through the expression of a coat protein from PRSV [16]. The development of the transgenic cultivar successfully averted the devastating loss of the papaya industry caused by PRSV in Hawaii [17].

5. Nutrient Enhancement of Staple Crops

Staple crops, such as rice, contain low levels of beneficial phytonutrients (nutraceuticals) and micronutrients, often below the recommended daily allowance [18]. In 2020, it was estimated that nearly 10% of the world's population (around 768 million people) were undernourished. More than half of all undernourished people live in Asia (418 million), while more than a third live in Africa (282 million) and a smaller proportion (60 million) in Latin America and the Caribbean [19]. Low- and middle-income countries rely more on starchy food staples, such as rice, banana (*Musa* spp.), cassava (*Manihot esculenta*), and corn. However, the majority are deficient in beneficial phytonutrients and micronutrients. The adoption of biotechnology is believed to offer an effective and sustainable strategy to produce GM biofortified crops with specific nutrient-enriched content. This is particularly important in countries where technology is urgently needed to help alleviate nutrient-deficiency-related illnesses [20].

There has been considerable progress in developing biofortified staple crops, predominantly via synthetic metabolic engineering [21]. The best-known example, and the first biofortified staple crop utilizing this method, is the β-carotene-enriched 'Golden Rice' [22]. The bioavailability of the β-carotene in rice, a precursor of provitamin A, could reduce vitamin A deficiency, which affects an estimated 190 million preschool-age children worldwide, of whom 91.5 million reside in Southeast Asia [23]. The Golden Rice was produced by introducing the entire β-carotene biosynthetic pathway through the multigene transformation of rice endosperm on two T-DNAs [24]. The first T-DNA carried the daffodil (*Narcissus pseudonarcissus*) phytoene synthase gene, *NpPSY1*, and the bacterial (*Erwinia uredovora*) phytoene desaturase gene, *EuCRT1*, controlled by an endosperm-specific glutelin (Gt1) promoter and constitutive cauliflower mosaic virus (CaMV) 35S promoter, respectively. The second T-DNA carried the daffodil lycopene β-cyclase, *NpLYC-b* gene under the control of a rice glutelin promoter and a selectable marker. While the β-carotene enhancement in rice was successful, the carotenoid concentration was only increased by 1.6 µg/g dry weight (DW) [24]. This prompted the production of 'Golden Rice 2′ (GR2), where the rice was engineered with corn *ZmPSY* and *E. uredovora EuCRTI* genes, both controlled by the native rice glutelin promoter [25]. The GR2 form contains a higher carotenoid accumulation of up to 23-fold (about 37 µg/g DW) than the original Golden Rice. Although GR2 is registered as safe in Australia, the USA, Canada, and New Zealand

and possesses import approvals, the Philippines is the only country so far that has authorized the direct use of GR2 in food, feed, and processing. Since the production of GR2, increases in β-carotene levels through GM technology have been observed across an array of food crops, such as sorghum, corn, wheat, banana, and canola [26].

The successful generation of biofortified crops that involved the simultaneous expression of multigenes, with some generating multiple essential nutrients, was also reported. Enhancement of multiple vitamins, such as β-carotene, folate, and ascorbate, in the rice endosperm was achieved through the introduction of *ZmPSY1* and *EuCRTI* (carotenoid pathway), rice dehydroascorbate reductase, *OsDHAR* (ascorbate pathway), and *folE* (folate pathway) using an unlinked direct DNA transfer co-transformation strategy [27]. In a more recent study, multi-nutrient biofortified rice was developed by expressing *Arabidopsis thaliana NICOTIANAMINE SYNTHASE1* (*AtNAS1*), *Phaseolus vulgaris FERRITIN* (*PvFERRITIN*), bacterial *CRT1,* and *ZmPSY* in a single genetic locus that increased the levels of iron, zinc, and β-carotene content in the rice endosperm [28]. In an example that employed the multigene stacking strategy, the production of ‘second generation’ folate (Vitamin B_9)-biofortified rice was achieved through simultaneous expression of four transgenes (*GTPCHI*, *ADCS*, *FPGS*, and *FBP*) [29]. Through this strategy, the folate content was increased significantly by 150-fold and has improved stability during post-harvest storage. Hence, this showed that the multigene stacking strategy is a highly efficient method for folate biofortification in rice, since the expression of a single transgene *GTPCHI* led only to about a 10-fold increase of folate concentration, whilst the co-expression of *GTPCHI* and *ADCS* resulted in a 100-fold folate enhancement [30].

6. Production of Plant-Based Pharmaceuticals

Global immunization coverage has declined from 86% in 2019 to 83% in 2020 due to the lack of access to immunization, aggravated by the straining of health systems due to the COVID-19 pandemic [31]. Children have been particularly affected, with the number of completely unvaccinated children increasing by 3.4 million in 2020 [31]. Vaccination coverage, specifically in underdeveloped countries, may be increased by developing a plant-based vaccine or ‘edible vaccine’. This innovation offers an exciting alternative by delivering a vaccine that can be easily administered and stored without refrigerated conditions [32]. An edible vaccine is produced by integrating specific genes encoding the desired antigenic protein into the plant host genome. Once the plant-derived vaccine is consumed, the release of antigens will stimulate a specific autoimmune response via mucosal immunity. Various candidates for plant-derived vaccines using economically important crops are currently under development, such as potato [33] and banana [34] expressing hepatitis B vaccine, tomato expressing triple vaccines against shigellosis, anthrax, and cholera [35], spinach (*Spinacea oleraceae*) expressing HIV-1 vaccine [36] and carrot (*Daucus carota*) expressing *Helicobacter pylori* vaccine [37]. An identical technique has been applied in chloroplast transformation, allowing a much higher accumulation of antigen protein because of the multi-copy nature of the chloroplast genome compared to the single-copy nature of the nuclear genome [38].

References

1. Grassini, P.; Eskridge, K.M.; Cassman, K.G. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nat. Commun. 2013, 4, 2918.
2. Alexandratos, N.; Bruinsma, J. World Agriculture Towards 2030/2050: The 2012 Revision; FAO: Rome, Italy, 2012.
3. Brookes, G.; Barfoot, P. GM crop technology use 1996-2018: Farm income and production impacts. GM Crops Food 2020, 11, 242–261.
4. Klumper, W.; Qaim, M. A meta-analysis of the impacts of genetically modified crops. PLoS ONE 2014, 9, e111629.
5. Li, M.; Xu, J.; Gao, Z.; Tian, H.; Gao, Y.; Kariman, K. Genetically modified crops are superior in their nitrogen use efficiency-a meta-analysis of three major cereals. Sci. Rep. 2020, 10, 8568.
6. Beatty, P.H.; Shrawat, A.K.; Carroll, R.T.; Zhu, T.; Good, A.G. Transcriptome analysis of nitrogen-efficient rice over-expressing alanine aminotransferase. Plant Biotechnol. J. 2009, 7, 562–576.
7. Good, A.G.; Johnson, S.J.; De Pauw, M.; Carroll, R.T.; Savidov, N.; Vidmar, J.; Lu, Z.; Taylor, G.; Stroeher, V. Engineering nitrogen use efficiency with alanine aminotransferase. Canad. J. Bot. 2007, 85, 252–262.
8. Pellegrino, E.; Bedini, S.; Nuti, M.; Ercoli, L. Impact of genetically engineered maize on agronomic, environmental and toxicological traits: A meta-analysis of 21 years of field data. Sci. Rep. 2018, 8, 3113.
9. Qaim, M. Bt cotton, yields and farmers’ benefits. Nat. Plants 2020, 6, 1318–1319.
10. Alvarez, F.; Manalo, A.; Clarete, R. Economic assessment of GM corn use in the Philippines. Int. J. Food Sci. Agric. 2021, 5, 115–128.

11. Sexton, S.E.; Zilberman, D. Land for food and fuel production: The role of agricultural biotechnology. In The Intended and Unintended Effects of U.S. Agricultural and Biotechnology Policies; Zivin, J.S.G., Perloff, J.M., Eds.; University of Chicago Press: Chicago, IL, USA, 2011; pp. 269–288.

12. Brookes, G.; Barfoot, P. Environmental impacts of genetically modified (GM) crop use 1996–2018: Impacts on pesticide use and carbon emissions. GM Crops Food 2020, 11, 215–241.

13. Savary, S.; Willocquet, L.; Pethybridge, S.J.; Esker, P.; McRoberts, N.; Nelson, A. The global burden of pathogens and pests on major food crops. Nat. Ecol. Evol. 2019, 3, 430–439.

14. Abel, P.P.; Nelson, R.S.; De, B.; Hoffmann, N.; Rogers, S.G.; Fraley, R.T.; Beachy, R.N. Delay of disease development in transgenic plants that express the tobacco mosaic virus coat protein gene. Science 1986, 232, 738–743.

15. van Esse, H.P.; Reuber, T.L.; van der Does, D. Genetic modification to improve disease resistance in crops. New Phytol. 2020, 225, 70–86.

16. Ferreira, S.A.; Pitz, K.Y.; Manshardt, R.; Zee, F.; Fitch, M.; Gonsalves, D. Virus coat protein transgenic papaya provides practical control of Papaya ringspot virus in Hawaii. Plant Dis. 2002, 86, 101–105.

17. Gonsalves, C.; Lee, D.; Gonsalves, D. Transgenic virus-resistant papaya: The Hawaiian 'rainbow' was rapidly adopted by farmers and is of major importance in Hawaii today. APSnet Feature Artic. Available online: https://doi.org/10.1094/APSnetFeature-2004-0804 (accessed on 5 March 2022).

18. Kasote, D.; Sreenivasulu, N.; Acuin, C.; Regina, A. Enhancing health benefits of milled rice: Current status and future perspectives. Crit. Rev. Food Sci. Nutr. 2021, 1–21.

19. FAO; UNICEF; WFP; WHO. The State of Food Security and Nutrition in the World 2021: Transforming Food Systems for Food Security, Improved Nutrition and Affordable Healthy Diets for All; FAO: Rome, Italy, 2021; Volume 1, pp. 1–240.

20. De Steur, H.; Mehta, S.; Gellynck, X.; Finkelstein, J.L. GM biofortified crops: Potential effects on targeting the micronutrient intake gap in human populations. Curr. Opin. Biotechnol. 2017, 44, 181–188.

21. Zhu, Q.; Wang, B.; Tan, J.; Liu, T.; Li, L.; Liu, Y.G. Plant synthetic metabolic engineering for enhancing crop nutritional quality. Plant Commun. 2020, 1, 100017.

22. Mallikarjuna Swamy, B.P.; Marundan, S., Jr.; Samia, M.; Ordonio, R.L.; Rebong, D.B.; Miranda, R.; Alibuyog, A.; Rebong, A.T.; Tabil, M.A.; Suralta, R.R.; et al. Development and characterization of GR2E Golden rice introgression lines. Sci. Rep. 2021, 11, 2496.

23. World Health Organization (WHO). Global Prevalence of Vitamin a Deficiency in Populations at Risk 1995–2005: WHO Global Database on Vitamin a Deficiency; WHO: Geneva, Switzerland, 2009.

24. Ye, X.; Al-Babili, S.; Klöti, A.; Zhang, J.; Lucca, P.; Beyer, P.; Potrykus, I. Engineering the provitamin a (beta-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. Science 2000, 287, 303–305.

25. Paine, J.A.; Shipton, C.A.; Chaggar, S.; Howells, R.M.; Kennedy, M.J.; Vernon, G.; Wright, S.Y.; Hinchliffe, E.; Adams, J.L.; Silverstone, A.L.; et al. Improving the nutritional value of golden rice through increased pro-vitamin a content. Nat. Biotechnol. 2005, 23, 482–487.

26. Garg, M.; Sharma, N.; Sharma, S.; Kapoor, P.; Kumar, A.; Chunduri, V.; Arora, P. Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. Front. Nutr. 2018, 5, 12.

27. Naqvi, S.; Zhu, C.; Farre, G.; Ramessar, K.; Bassie, L.; Breitenbach, J.; Perez Conesa, D.; Ros, G.; Sandmann, G.; Capell, T.; et al. Transgenic multivitamin corn through biofortification of endosperm with three vitamins representing three distinct metabolic pathways. Proc. Natl. Acad. Sci. USA 2009, 106, 7762–7767.

28. Singh, S.P.; Gruissem, W.; Bhullar, N.K. Single genetic locus improvement of iron, zinc and beta-carotene content in rice grains. Sci. Rep. 2017, 7, 6883.

29. Blancquaert, D.; Van Daele, J.; Strobbe, S.; Kiekens, F.; Storozhenko, S.; De Steur, H.; Gellynck, X.; Lambert, W.; Stove, C.; Van Der Straeten, D. Improving folate (vitamin B9) stability in biofortified rice through metabolic engineering. Nat. Biotechnol. 2015, 33, 1076–1078.

30. Storozhenko, S.; De Brouwer, V.; Volckaert, M.; Navarrete, O.; Blancquaert, D.; Zhang, G.F.; Lambert, W.; Van Der Straeten, D. Folate fortification of rice by metabolic engineering. Nat. Biotechnol. 2007, 25, 1277–1279.

31. World Health Organization (WHO). Immunization Coverage. Available online: https://www.who.int/news-room/fact-sheets/detail/immunization-coverage (accessed on 4 January 2021).

32. Kurup, V.M.; Thomas, J. Edible vaccines: Promises and challenges. Mol. Biotechnol. 2020, 62, 79–90.

33. Rukavtsova, E.B.; Rudenko, N.V.; Puchko, E.N.; Zakharchenko, N.S.; Buryanov, Y.I. Study of the immunogenicity of hepatitis B surface antigen synthesized in transgenic potato plants with increased biosafety. J. Biotechnol. 2015, 203, 84–88.
34. Kumar, G.B.; Ganapathi, T.R.; Revathi, C.J.; Srinivas, L.; Bapat, V.A. Expression of hepatitis B surface antigen in transgenic banana plants. Planta 2005, 222, 484–493.
35. Davod, J.; Fatemeh, D.N.; Honari, H.; Hosseini, R. Constructing and transient expression of a gene cassette containing edible vaccine elements and shigellosis, anthrax and cholera recombinant antigens in tomato. Mol. Biol. Rep. 2018, 45, 2237–2246.
36. Karasev, A.V.; Foulke, S.; Wellens, C.; Rich, A.; Shon, K.J.; Zwierzynski, I.; Hone, D.; Koprowski, H.; Reitz, M. Plant based HIV-1 vaccine candidate: Tat protein produced in spinach. Vaccine 2005, 23, 1875–1880.
37. Zhang, H.; Liu, M.; Li, Y.; Zhao, Y.; He, H.; Yang, G.; Zheng, C. Oral immunogenicity and protective efficacy in mice of a carrot-derived vaccine candidate expressing UreB subunit against Helicobacter pylori. Protein Expr. Purif. 2010, 69, 127–131.
38. Lossl, A.G.; Waheed, M.T. Chloroplast-derived vaccines against human diseases: Achievements, challenges and scopes. Plant Biotechnol. J. 2011, 9, 527–539.