Review article

The Impact of Biotechnology in shaping the Modern Agriculture

Abstract

Advances in biotechnology have created new opportunities for food diversity in terms of both quantity and quality, as well as for collecting food in proportion to the world's expanding population and ensuring food security. With the advancement of molecular biology, DNA sequencing, and recombinant DNA in the middle of the 20th century, modern-day advancement of molecular breeding gave rise to genetic engineering and recombinent DNA techniques that are today frequently connected to biotechnology. This expansion has been facilitated by a variety of fields, including genetics, molecular biology, and biotechnology. The use of genetic engineering in agriculture has grown due to its ability to precisely create and insert a gene from any living organism. Molecular markers are also utilized to identify disease and pest resistance in order to increase agricultural output using traditional techniques. Genetic engineering plays a crucial role in agriculture, representing the scientific and technical advancement of traditional methods for crop enhancement. Recombinant DNA technology, RNA interference, and CRISPR genomic editing are some of the instruments and methods used in genetic engineering. The emergence of biotechnological innovations aimed at improving the nutritional composition of individual foods has led to the growing problem of a malnourished world population, where a growing number of people rely on large regions of the world for food used as the only source of protein, carbohydrates, fats and several essential minerals and vitamins, in addition to being a source of energy.

Keywords: biotechnology, food security, genetic engineering plant health management

1 Introduction of Agricultural Biotechnology

Biotechnology has made agriculture a completely different sector from what it used to be prior to the scientific and technological revolution. The new developments in science and technology have opened up new frontiers in not only harvesting food proportionate with the ever-growing global population and meeting the food security needs, but also in the diversity of food in terms of quantity and quality. These novel technologies have demonstrated successful means of developing a plant protection system by taking effective control of new pests and conferring resistance to grown crop plants against disease-causing pathogens and also abiotic stresses (Zsögön*et al.*, 2022; Haris *et al.*, 2023). These developments are explained using molecular immunization, whereby the defensive capabilities of plants are heightened against diseases. Traditionally, agriculture has been defined as an art and a science of crop production and livestock rearing. It aimed at high yield, better quality, as well as profitability. Precision of operations such as tillage, irrigation, nutrient application, plant health management, and crop harvesting depended on the wisdom supported by the experience of the farmers.

2. Historical Background of Biotechnology in Agriculture

While practiced in a rudimentary form by early human populations, agriculture has evolved into a global system by which societies produce food. Various social, religious, and technological attributes have influenced the practice of agriculture over time, which led to the implementation of selective breeding and hybridization in animal and plant systems. The advent of modern biology in the mid-20th century, through the introduction of molecular biology, DNA sequencing, and recombinant DNA, resulted in the development of genetic engineering methods that are now commonly associated with biotechnology. The particular impetus of genetic engineering was the Green Revolution and its focus on increasing crop production. Current research has moved away from this original goal to topics such as increasing the nutritional density of foods, developing genetically engineered proteins as pharmaceutical agents, and understanding the crop plant as a model. Agricultural biotechnology is restricted by the social environment in which it operates (Hanlon & Sewalt, 2021; Jin et al., 2021). The biotechnologies discussed here will impact future agricultural practices and are limited in their application by the abilities of the public sector to provide further biological and physical data. Finally, future biotechnological applications are heavily influenced by the successes and failures of the Green and Gene Revolutions in which they operate. Agricultural biotechnology has seen a rapid advent since the discovery of the double helix in 1953. Many areas, such as biotechnology, molecular biology, and genetics, have contributed to this growth. However, agricultural biotechnology is determined not solely by scientific advances but also by the political and social framework within which it operates. National biological legislation, international agreements, regulations, corporate sponsorship, and perceived social value all influence which biotechnologies are developed.

3. Key Biotechnologies Used in Agriculture

Extensive progress happening at the molecular level results in the use of a variety of biotechnologies in agriculture. Genetic biotechnology, which can specifically design and introduce a gene from any living organism, has expanded its applications in agriculture. Thanks to tissue culture techniques, which are used to rapidly propagate a plant from a single cell or small group of cells, many problems in the production of disease-free plants, timely and in appropriate quantities, have been resolved. Plant regeneration through tissue culture is used to propagate bananas, potatoes, sugarcane, strawberries, and apples, which are crops with low sexual seed. To shorten the breeding plant generation lifecycle, transgenic technology is used in a tissue culture system. To improve agricultural production through conventional methods, molecular markers are also used. By using a molecular marker, a plant can display a combination of favorable traits in the same variety. Markers are also used to detect the presence of disease and pest resistance in plants (Andualem and Seid, 2021; Riley & Guss, 2021).

Breeding for disease and pest resistance is a sustainable approach. In doing this, the DNA from one living organism is cut and introduced into another organism. In this process, the inactivated genes are activated and the beneficial protein is produced. From the technical point of view, this biotechnology is promising to improve livestock, but it is not currently used in practice due to problems in the area of ethics and regulations. Biotechnology in agriculture aims to help increase food production, improve the efficiency of food production, and provide food with better quality and safety for a large number of people. Several examples of biotechnological applications in agriculture will be presented in the next subsection. To match biotechnological trends, farmers should update themselves on new scientific and technical advances and socio-economic trends. Biotechnological applications in biological methods for sustainable crop production fit with the current trend and are suitable for the Agro-Ecological Zone Enhancement approach (Qaim, 2020; Munawar et al., 2020).

3.1. Genetic Engineering

Genetic engineering involves changing the genetic makeup of an organism in order to introduce valuable, desirable traits. In agriculture, genetic engineering is pivotal, marking the technological and scientific evolution of the classical strategies used for the improvement of various crops. Genetically Modified Organisms (GMOs), a true output of the development and genetic engineering, have been engineered with exclusive traits of interest, such as drought tolerance, pest resistance, enhanced quality, and high yield, to cater to the demands and challenges of modern agriculture. These GMOs or transgenics are thus used in modern agriculture for sustainable practices, to conserve the environment, and to boost human nutrition and wellness. The tools and techniques of genetic engineering include recombinant DNA technology, RNA interference, and genome editing via CRISPR genomic editing (Mueller & Flachs, 2022; Tian *et al*., 2021). The first-ever genetically engineered crop was Florida's transgenic tomato, released in 1994, with a shelf life exceeding that of normal tomatoes due to the overexpression of the polygalacturonase gene. Several GM crops have now made their mark in agriculture and are approved by various mechanisms.

There are reportedly 17 times more biotech-planted global acreage now than there was in 1996, with an average annual biotech growth rate of 6%. Between 1996 and 2018, biotech gains of $225.1 billion were realized globally, with 44 percent in developing countries. Biotechnology will, therefore, support diverse ways to keep meeting food and nutrition needs for humanity via efficient practices. The construction of a transgenic crop plant involves several stages, including the transformation of the plant and selection of transformed plant material to regenerate a transformed plant. The development of a transgenic plant to be ready for commercial release typically requires 8 to 14 years, depending on the regulatory environment and the plant species. Despite the benefits that GMOs are reported to have, there is much opposition to their use. Due to public acceptance, GMO crops have failed to gain access to some markets. Ethical issues, public concern, and regulatory compliance have all been involved in the ongoing debate over biotechnology acceptance (Biswas et al., 2021; Deconinck, 2020). For example, stakeholders are concerned about GMO biosafety, intellectual property rights, trade, environmental concerns, and environments that are GMO-free. Regulatory concerns derive from GMO application requests that require months or even years to be accepted or rejected. Policies concerning labs, smallholders, large commercial entities, NGOs, governments, etc., can be periodic one-off symposiums, consultations, workshops, papers, etc. Although in some situations the public is completely opposed to GMOs, in others it is more receptive.

4. Benefits of Biotechnology in Agriculture

Biotechnology enables solutions for improving food production, making it more sustainable and environmentally and socially acceptable. The application of biotechnology to agriculture can be expected to increase the ability of crops to withstand pests and diseases, as well as ordinary pests and other factors with harmful effects on crops. A long-term goal pursued by many projects is the development of plant varieties that can withstand climate fluctuations. Biotechnological progress thus contributes to the realization of the concept of sustainable agriculture for the future. The most common types of biotechnology that the largest number of projects support are the production of transgenic varieties of plants and the modification of crop quality (Andualem and Seid, 2021; Khan et al., 2021).

The increasing problem of a malnourished world population, in which more and more people depend on large regions of the world for rations used not only as a source of energy but also as the only source of protein and several essential vitamins, results from the development of biotechnological innovations aimed at improving the nutritional composition of individual foods. Additionally, with these varieties approved and grown in several developing countries in 2020, there are some economic benefits: increased farmer income and reduced production costs through reduced use of pesticides. The accumulated annual increase in production for the 35 countries included in this report in 2020 was an estimated 231.3 million tons of plant matter for the 15-year period from 1996. Over the entire period, this represents a reduction in greenhouse gas emissions. Perhaps the most notable implication of these studies is that innovation is ongoing in agriculture, and biotechnologies of the future may provide benefits to farmers and consumers. Continued research will be essential (Augustin et al., 2024); McClements et al., 2021).

4.1. Increased Crop Yields

Increased crop yields constitute an essential component of biotechnology's potential to increase the productivity of agriculture, a phrase that refers to the amount of crop production obtained on a given amount of land. Productivity can increase through various means: producing on new lands or more hectares sown per year; introducing additional crops per year or biannual production; achieving higher yields for the same lands; and increasing supply factors such as seed, fertilizer, pesticides, machinery, capital, and technical progress—technical knowledge over the long term and facilitates per acre of land, or any combination of these. For the purposes of our analysis, we highlighted increased yields as the primary dimensional mechanism by which agricultural biotechnology can increase the productivity of agriculture. Yield intensity is spurred by a variety of practices and factors, ranging from improved soil fertility via better irrigation practices to the adoption of high-yielding crop varieties and reductions in crop waste. Biotechnological innovations have spawned a new plethora of crop varieties that are capable of boosting yields. A prominent example of such varieties is genetically modified crops engineered to achieve high yields (Kasera et al., 2021; Esiobu & Virgin, 2022). These crops come in a variety of types: drought-resistant and salt-tolerant crops, pest-resistant soy, maize, and cotton that have been engineered in a laboratory to produce their own insecticides, and herbicide-tolerant crops—dominant varieties of GM crops engineered by multinational agricultural biotechnology corporations.

7. Case Studies of Successful Biotechnological Applications in Agriculture

Case studies are widely used to profile successful applications of biotechnology in agriculture. The majority of case studies present successful results and focus on developed agricultural countries. This can be viewed as a positive sign providing confidence to the reader, although the downside is that negative results are only sporadically introduced, hindering a balanced assessment. Furthermore, assessing and comparing the potentially negative aspects of the discussed successes would help readers learn more about best practices and potential pitfalls. Nevertheless, the presented case studies offer evidence of the successful and transformative potential of biotechnology in agriculture. Crops with increased resistance to pests can lead to less insecticide spray, safer working conditions, increased crop yield, and increased farmers' income. Other case studies focus on the reduced presence of diseases in animals as another protective strategy. It is clear that some of the case studies should have been included in different categories, since the content focuses on increased quality and safety with possibly increased health benefits related to function and not 'more'. A number of case studies in the area of drought resistance are considered benefits, which were used in two sections to provide a complete overview of certain applications.

The majority of the case studies portray successful results and do not give much insight into negative topics. The content is limited to developed countries due to an increased level of technological development and governmental financial backing. The countries concerned are China, which earns the biggest revenue in comparison with other countries. In addition to the USA, where agricultural biotechnology has claimed the biggest profit beside the pharmaceutical industry, Argentina, Canada, India, Burkina Faso, the Philippines, and the Czech Republic offer compelling case studies. There is an increased level of information on plant biotechnology followed by animal biotechnology, due to increasing consumer interest in genetically developed produce. Collaboration is essential for the commercial success of GM products. It has been shown that at local levels in particular, collaboration is required. Consequently, researchers need to be kept up-to-date in order for them to understand and come up with the necessary alterations to technology. According to other respondents, the implementation of the technology is frequently led by the companies, thereby addressing the identification of markets where biotech food is likely to be accepted. For effective knowledge transfer, a good communication strategy is driven by organizing seminars and workshops, which is supported by other graphical perceptions such as films, visualization, working visits, demonstrating experiments, and yearly symposiums. Concerning case studies, communication was perceived as being expensive because of the cost implications this has for awareness materials and setting up round tables, meetings, and large, expensive conferences. The community partnership has established the biotechnology test field meeting, and there is also evidence of global cooperation for communication strategies. Furthermore, economic profitability is necessary in biotechnological partnerships. It is more likely that partnerships are formed with companies, as they are targeting the same objectives of yield improvement and quality tests, and are therefore considered to provide common working frames and developments.

7.1. GMO Crops

Since the late 1990s, biotechnology has provided powerful tools for the radical overhaul of agriculture and how it is practiced. Genetically modified crops bearing traits that protect against abiotic stresses, enhance nutritional content, and increase yields have been the most immediately substantial commercial outcomes in agriculture. The development of each profitable trait can cost over a reported 150 million US dollars. The first GMO to be commercialized and grown in the field was a virus-resistant tobacco plant in 1986. GMO crops are cultivated on 2.84 billion hectares, three-quarters of which are grown in the Americas, and half of this area is planted with herbicide-resistant plants. Crops have been modified to develop certain desirable traits, such as: 1) resistance to fungal pathogens or crop-destroying virus vectors, 2) resistance to pesticides in the farm or herbicide-resistant GM crops, 3) food modification to reduce the crop's photosynthetic and respiratory pathways, 4) nutritional modification by adding genes that produce vitamins, pharmaceutical compounds, vaccines, and other medications, and 5) all healthy, productivity-enhancing, and beneficial traits, and to cure the problem of micronutrients in a growing plant (Qaim, 2020). As of the end of 2019, about 45 different GMO crops were cultivated, with 151 transgenic events. Many of these crops have been successful in the market, revolutionizing modern agricultural methods. These include maize, cotton, soya, rapeseed, and sugar beet. For example, over 88% of maize and cotton cultivated in the United States is GM, and in Brazil, 93.5% of their cultivated soya is GM. The nutritional and potential medical benefits of these GMOs cannot be underestimated. The popularity of these GMOs has clearly had a positive impact on the entire global population. However, the environmental impact of utilizing these GMOs has had, or will have, negative effects as well. This may include increasing pesticide resistance in weeds and creating insect resistance in pests, as well as the loss of beneficial and non-target bugs. Additionally, questions regarding the sustainability of this approach for increasing production have been raised given its potential impacts on health and biodiversity. In addition, a number of socio-economic issues may be attributed to the reduction of the cost of these genetically modified crops (Brookes & Dinh, 2021; Brookes & Barfoot, 2020).

8. Future Trends and Innovations in Biotechnology in Agriculture

Low crop yields are documented by the acceptance of ineffective soil management strategies and asymmetric nutrient management (Singh et al., 2023). There are several trends in the biotechnological industry that are constantly evolving and will likely shape the future of agriculture. One trend is in the field of gene editing. There are currently two practices being developed. These are using technology or knocking out specific genes. The second trend is in the field of synthetic biology. This practice aims to create new life forms from the bottom up that are better designed and built than natural organisms.

One particular technology that is currently booming is based on the expanding uses of an old technology but a new application. This consists of using old and new machine learning and data science methods to manage crop fields as precisely as possible. The ultimate aim is to answer the question of how to make each crop variable with the target of getting more food using fewer resources. Concomitantly, there is a growing need to develop innovations to face major hurdles to global agriculture brought on by climate change and other problems to ensure food security. For the plant breeding industry, this includes a big push for yield improvements and food quality using methods with a smaller detrimental effect on the environment. Academic research and the agribiotechnology industry, including big food, are placing renewed emphasis and investment on biotechnologically treating plants and crops for disease resistance, stress tolerance, and researching the benefits for the uptake of nutrients for both academic and financial gain. The development of windbreak trees as mitigation for effects on crops exemplifies future trends. In five to ten years, demands for developing biotechnology tools for the replacement of fertilizers and pesticides are likely to increase due to the increasing impact on crop production, human health, and the range of species, including beneficial insects, affected by agrochemicals (Batista & Singh, 2021; Thomas et al., 2020). Public-private partnerships and consortium designs are likely to be a more substantial driving force for academic researchers in biotechnology collaborations than single partnerships with industry. Increased globalization affects collaborations in biotechnology where academic corporations are multinational, as well as the private sector; however, legislation in terms of biotechnology regulatory decisions is still likely to remain internally contained in one country. Ethical concerns about employing biotechnology are likely to be translated differently in different countries. Ethical concerns regarding issues such as transformation and synthetic biology-based biotechnological research in plants are likely to still be controversial and debated in the public domain. Public support for missions to combat global warming and new technologies in agriculture is generally agreed upon in Europe, but currently, the use of innovative biotechnology is likely to be subjected to regulatory hurdles in Western society.

9. Conclusion

Biotechnology can have potential uses to enhance agriculture. First, through genetically modified crops, which allow increased productivity and more sustainable farming practices. Genetic modifications can also help plants adapt more easily to the expected climatic and biological stress factors. Even though genetic modifications are not a "magic bullet" to secure food supplies for growing populations and to make farming more sustainable, they have the potential for significant contributions to these goals if farmers, researchers, and policymakers can address some current challenges to their development and use. Ethical concerns of many people around the world must be considered, regulations dealing with sources and pre-release tests to ensure the safety of genetically modified plants for people and the environment need to be perfected, and the debate on these issues needs to become more balanced and less polarized. This will require ongoing research to answer outstanding questions about the safety and efficacy of genetically modified crops.

There is increasing investment in the development of crops based on genetic modifications. The potential of biotechnology to enhance agriculture in the future must not be compromised through poor communication and regulation of current developments. Clearly, there is more than a research and development agenda to pursue, but also a public engagement agenda to be acted upon. One major constituency in agriculture, however, must see benefits emerging from responsible and well-resourced applications of biotechnology research and development. This is the constituency of farmers across the developing and industrialized worlds who are responsible for putting food on our plates. It is making a contribution to their own enterprises that those who are organizing their voice see as well worth supporting.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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