

Role of biotechnology in creating sustainable agriculture

S. Sharaniya¹ and P. Loganathan²

Department of Bio-Science, Faculty of Applied Science Vavuniya Campus, University of Jaffna, Sri Lanka

Article Info

Received: 29-12-2025 Revised: 12-01-2026 Accepted: 10-02-2026 Published: 16-03-2026

Abstract

essential to achieve a balance between social duty, environmental stewardship, and economic success. This can be challenging, particularly when dealing with biotic and abiotic challenges such illnesses, pests, soil degradation, water depletion, and climate change. One of the biggest challenges to sustainable agriculture is the proliferation of pests and illnesses that may drastically reduce crop yields and quality. To solve these problems, biotechnology can be utilised to develop crops that are resistant to diseases and pests. Another barrier to sustainable agriculture is soil nutrient deficiency, which can lower plant health and crop output. The development of more productive and nutrient-dense crops might be greatly aided by biotechnology. On the other hand, it is crucial to make sure that these technologies are developed responsibly and that their advantages are shared fairly among groups and geographical areas.

1.0. Introduction

The goal of sustainable agriculture is to provide society's needs for food and fibre in an environmentally responsible way that doesn't interfere with natural processes or ecosystems. To create sustainable, climate-resilient agriculture, social and economic equality must be integrated with economic viability and a healthy environment. With the potential to boost productivity, biotic and abiotic resistance, and nutrient-rich crops, biotechnology has become a promising technique in agricultural enhancement. The word "sustainable" comes from the verb "sustain," which means to support, endure, and preserve. Sustainable agricultural development aims to provide long-term solutions for present and future generations in order to satisfy society's needs for food and fibre. The development of climate-resilient agriculture and the integration of economic profitability and a healthy environment with social and economic equality are the main prerequisites for sustainable agriculture. Sustainable agricultural scientists must employ interdisciplinary methods that integrate biology, engineering, chemistry, economics, and community development in order to achieve this aim. Sustainable agriculture is defined by the 1990 Farm Bill (The Food, Agriculture, Conservation, and Trade (FACT) Act of 1990) as an integrated system of plant and animal production practices with a site-specific application that will, over time, satisfy the following needs: (a) provide food and fibre; (b) improve environmental quality by judiciously using natural resources; (c) make the most efficient use of on-farm resources by integrating regenerative approaches; (d) improve farm economics; and (e) improve the quality of life for farmers and society at large [1-3].

In order to increase agricultural output and resilience to a variety of biotic and abiotic challenges, biotechnology—a technical application in biology—mainly entails the transfer of genetic material having a particular feature from

one crop or organism to another. Numerous studies conducted on farms and small plots have shown that biotechnology intervention can enhance crop production, nutrient quality, and weed control [4, 5] without having an adverse effect on the environment or ecosystem. Weed control is made easier and more effective by engineered crops, such as glyphosate-resistant crops [6]. It is possible to reduce the need of synthetic pesticides by engineering the crop to have disease resistant qualities. By adding genes relevant to particular metabolic processes, crops can be biofortified. For example, Golden Rice was fortified by adding genes for beta-carotene production [7]. More prospects and optimism for creating the second or third generation of biotechnological goods have been made possible by recent developments in OMICS techniques, particularly CRISPR genome editing. Despite biotechnology's potential in sustainable agriculture, public opinion continues to be a barrier. To address people's questions and concerns, further outreach and extension are required. The widespread use of biotechnology in agriculture is hampered by the possible dangers of genetically modified organisms and the requirement to protect biodiversity.

Improved agricultural management, plant breeding, fertiliser technology, and farm mechanisation have all contributed to the 21st-century agricultural revolution, which has significantly increased crop productivity. However, given recent reports of yield stagnation and increased yield variability, agricultural output may be impacted by climate change, biotic and abiotic stress, biodiversity losses, and soil degradation. The yield of four key global crops—maize, rice, wheat, and soybeans—increased by 1.6%, 1.0%, 0.9%, and 1.3% annually, respectively, according to a research by Ray and colleagues [8]. This is less than the 2.4% yearly expansion.

necessary pace to satisfy the growing population's need. By 2030, there will be nine billion people on the planet, and the planet will be warmer. Biotechnology will play a crucial role in addressing concerns related to food security and climate change.

In sustainable agriculture, biotechnology has great promise for enhancing soil health and nutrient cycling. To improve soil fertility and structure, inhibit plant diseases, and encourage plant development, some microorganisms can be introduced to the soil. Examples of using natural resources to improve soil health, plant health, and production are biofertilizers and biopesticides. Biotechnology offers several chances to improve agricultural production, quality, and sustainability, and it has enormous promise in sustainable agriculture.

2.0 Sustainable vs conventional farming Before talking about the possible role of biotechnology in increasing agricultural output, it is important to understand conventional and sustainable agriculture systems, their drawbacks, and their advantages. From traditional farm practices to modern intensive agriculture, the definition and importance of conventional agriculture have changed over time. Among the many challenges facing agriculture are climate change and various forms of environmental degradation, including soil degradation and abiotic and biotic stresses. Sustainable agriculture places a strong emphasis on stewardship and protection of soil, environment, and ecosystem in order to address these issues. Sustainable agriculture includes agricultural methods that are socially acceptable, economically feasible, productive, and ecologically sound. However, because sustainability encompasses a way of thinking and farming techniques, it is difficult to describe. Two perspectives exist about sustainable agriculture.

One perspective calls for the adoption of technology that lessen the negative impacts of conventional farming in order to transform current conventional agriculture into more cautious and efficient farming methods. The opposing viewpoint is that agriculture has to be fundamentally altered by incorporating social values [10]. From a wider angle, two opposing paradigms in the agricultural environment are

exemplified by conventional and sustainable agriculture. The former is primarily dependent on the use of sophisticated technologies and synthetic inputs and is characterised by a desire toward yield maximisation and financial benefit. Sustainable agriculture, on the other hand, promotes a balanced ecological strategy that emphasises optimised yields combined with the maintenance and improvement of soil health, water quality, and biodiversity [11]. One of the main differences between these two farming methods is the impact on the environment. Because traditional agriculture is inherently resource-intensive, it frequently results in contamination through nutrient losses and soil structure loss, which causes soil deterioration, erosion, and pollution of the air and water [12,13]. By using techniques like organic farming, crop rotation, conservation tillage, and natural fertiliser application, sustainable agriculture, on the other hand, promotes the preservation and improvement of natural resources essential to farming operations [14].

These agricultural practices are further distinguished by their economic ramifications. Conventional farming methods usually place a strong emphasis on quick financial gains and the use of mechanisation, which can spur output improvements but also come with significant expenditures, raising the possibility of farmer debt. By promoting the effective use of natural resources and placing a high priority on improving soil health, sustainable agriculture, on the other hand, may reduce costs and eventually promote increased long-term yields and profitability [15].

In order to preserve healthy ecosystems and the long-term viability of agricultural methods, sustainable agriculture prioritises the conservation and improvement of biodiversity [16]. Crop rotation, cover crops, intercropping, and using natural predators to control pests are all key components of sustainable agriculture. Larger crop yields are often produced by traditional agriculture, but this comes at a significant environmental cost and raises concerns about the sustainability of such methods [13]. Sustainable agriculture, on the other hand, aims to protect and improve the natural resources that are essential to farming, support biodiversity, and ensure farmers' long-term financial sustainability. The main objective of sustainable agriculture is to create and maintain environments that support current and future generations by enabling the fruitful coexistence of humans and nature. To do this, one must comprehend the mechanics behind natural

systems, their role in maintaining ecological balance, and an acknowledgment of humanity's reliance on these resources to uphold our contemporary lifestyles [17].

2.0 What does it need to be sustainable?

A sustainable agriculture should be economically sustainable and environmentally sound with societal values, and it should be able to provide sufficient food for the increasing population.

2.1. Economic sustainability

In this sense, "economically sustainable" refers to farming methods that are both economically feasible and provide enough revenue for farmers or those engaged in food production and processing to sustain their way of life. To guarantee that everyone has access to wholesome food and a healthy life, economic sustainability is essential [18, 19]. The widespread adoption of sustainable practices will be encouraged by the financial reward. Economic sustainability in agriculture may be influenced by a number of important aspects, such as: Diversification: Increasing the variety of crops or animals raised can help lower the risk of losses brought on by bad weather, shifting market conditions, or disease outbreaks. Efficiency: Precision farming and conservation tillage are two examples of effective agricultural techniques that may lower expenses and boost profits.

Resource management: Long-term production can be increased and natural resources can be preserved with the use of sustainable agriculture techniques including soil management and water conservation. Market access: By giving farmers a variety of ways to sell their goods, access to local, regional, and global markets may support the economic viability of agricultural systems. Supportive institutions and policies: By fostering research and development, granting access to credit and other financial services, and enacting laws that encourage sustainable practices, governments and other organisations may advance economic sustainability in agriculture.

2.2. Environmentally safe and sound

Soil, water, and air are examples of natural resources that agriculture should protect since they are essential to human life, farms, and the environment. Food production can be improved and the natural environment can be preserved by working with natural resource systems rather than suppressing them [20,21]. Environmental sustainability in agriculture is influenced by a number of important issues, such as: a. Soil health: Conservation tillage and cover crops are two sustainable farming techniques that can assist maintain soil health and stop erosion. b. Water conservation: Water use and waste may be minimised with the use of irrigation systems like drip and precision irrigation.

c. Biodiversity: A variety of plant and animal species can be supported by fostering biodiversity on agricultural land through techniques like agroforestry and habitat conservation. d. Use of fertilisers and pesticides: Reducing the use of artificial fertilisers and pesticides can help safeguard natural resources and lessen pollution.

Renewable energy: Using renewable energy sources, such as solar or wind power, can help minimize agriculture's carbon footprint and safeguard the environment.

2.3. Societal values: Good for families and communities

Opportunities and cooperative connections between farmers' families and community people should be fostered via agriculture. For instance, a local food marketing system in community-supported agriculture gives people the chance to start farming without having to make a sizable initial commitment, gives family members a job on the farm, and establishes direct connections with local customers [22]. Economic, social, cultural, and environmental benefits are just a few of the societal values that agricultural sustainability may offer. a. Economic advantages: A sustainable agriculture sector may boost economic growth, provide wealth, and create jobs. b. Social benefits: By assisting rural communities and maintaining farming-related cultural customs, sustainable agriculture may have a positive social impact. Additionally, it can enhance access to wholesome food and advance food security, both of which have a good effect on public health. c. Cultural advantages: Sustainable agricultural methods may aid in the preservation and advancement of cultural customs, which can be a vital component of a community's cultural identity. d. Environmental benefits: Sustainable agricultural methods may lessen adverse environmental effects like pollution and greenhouse gas emissions while also protecting natural resources like soil and water. Both the environment and the people who depend on it may profit in the short and long terms from this.

2.4. Food and fiber security

In order to feed the growing population, sustainable agriculture must also be safe and adequate. A sustainable and secure food system will depend on enough food production, source reduction, redistribution, and recycling [23]. Food security may benefit from agricultural sustainability in a number of ways: a. Increasing productivity: Precision farming and conservation tillage with residue management are examples of sustainable farming techniques that can boost agricultural areas' productivity and enhance the amount of food available. b. Cutting waste: Increasing food availability may be achieved by using efficient agricultural methods and cutting food waste across the supply chain. c. Preserving natural resources: Long-term food production may be supported by conserving water and soil.

d. Increasing resilience: Sustainable agriculture may help guarantee the security of the food supply by being more adaptable to outside threats like pests or droughts.

3.0 Application of biotechnology for sustainable agriculture

Today, agricultural scientists face a major problem due to the world's population growth, resource scarcity, loss of useable land, climate change, and environmental degradation. Biotechnology will offer substitutes for existing strategies to enhance the environment and system of agriculture [24]. In the existing agricultural production system, biotechnology can decrease the use of pesticides and fertilisers. Soil, air, and water quality can be improved by using less inorganic fertilisers and pesticides. Developing various high-yielding and stress-tolerant crop types may be accomplished strategically via the use of biotechnology [25]. Clarifying the underlying molecular principles of various metabolic processes and using this information to increase agricultural and animal productivity have been the main goals of recent biotechnology research advances. Compared to traditional crossbreeding, genetic engineering provides a more accurate and efficient means of gene transfer. Herbicide, pest, and disease-resistant crop varieties may be created by genetic manipulation, which also improves the nutritional profile of crops. Plants with traits like drought, cold, and salinity tolerance can help farmers make use of previously useless land. Abiotic stress is a major barrier to agricultural output. Advanced plant breeding approaches are made possible by genetic mapping, which may efficiently screen for crucial features that are otherwise challenging to track using conventional breeding [26,27]. The ability to quickly produce numerous copies of cultivars using micropropagation can speed up the breeding of better varieties and aid in the conservation of germplasm [28]. In agricultural biotechnology, plants, animals, and microbes are modified via the use of scientific instruments and methods including genetic engineering, molecular biology, and micropropagation. Major obstacles to developing sustainable agriculture, such as producing enough food in the limited space (loss of usable lands), with limited resources (water scarcity), under various environmental stressors (drought, salinity, high temperature), and using less synthetic fertiliser and pesticides, could be solved by agricultural biotechnology. It is anticipated that ongoing biotechnology research will provide many more crop varieties with a wide range of agricultural applications. Farmers have been manipulating plants and animals with desired features through selective breeding for ages. Future developments might make it possible for biotechnology to give consumers longer-lasting, nutritionally enhanced meals. Biotechnology has the ability to improve soil quality through phytoremediation in addition to crop production. By creating hardier crops that flourish in challenging conditions with less fuel, labour, fertiliser, and water input, biotechnology can also help conserve natural resources, improve plant nutrient utilisation, decrease nutrient runoff, increase soil organic carbon sequestration, and meet rising food and land demands. Agricultural biotechnology has made it possible to create crops that are resistant to

Table 1. Different biotic/abiotic stress-resistant crops.

Characteristics	Crop	Reference
Insect resistance plant	Poplar 741	[29]
Virus resistance plant	Rainbow papaya, SunUP papaya	[30,31]
Herbicide resistance	Petunia hybrida (glyphosate tolerant)	[32]
Drought tolerant	Apple, tomato, potato	[32]
Salt tolerant	Apple, tomato	[32]
Biofortified	Rice, maize, potato	[33]
High yielding	Maize	[34]

devastating diseases. For instance, the papaya ringspot virus (PRSV) threatened the Hawaiian papaya industry until genetically engineered rainbow papayas resistant to the disease were created [31]. This breakthrough saved the US papaya industry, and research is ongoing for other crops such as potatoes, squash, and tomatoes, to provide resistance to viral diseases that are challenging to control. Biotech crops have the potential to increase farming profitability by improving crop yields, nutrient use efficiency, resistance to biotic and abiotic stress, and nutritional profile.

3.1. Yield improvement

Increasing agricultural productivity will be essential to ensuring food security as the world's population grows. Major yield-determining traits like photosynthesis, shoot-to-root biomass, inflorescence architecture, stomatal movement and density regulation, nutrient acquisition and use efficiency, microbial interactions, resistance to environmental stresses like drought, salinity, flooding, extreme temperature, and resistance to pests and pathogens can all be improved through genetic manipulation.

In comparison to the wild kinds, overexpression of the gene OsDREB1C can significantly improve rice production by 41.3% to 68.3%, according to a recent study. The yield is mostly dependent on how well plants absorb photosynthetically active solar energy and transform it into biomass. In rice, OsDREB1C gene expression reduced growth time, enhanced nitrogen usage efficiency, and encouraged resource allocation [35]. Rubisco is one of the main elements that determines a plant's photosynthetic efficiency. Because it converts atmospheric CO₂ into biomass and plays a significant role in the global carbon cycle, Rubisco is an essential enzyme for photosynthesis. But because it takes both CO₂ and O₂ as substrates and produces the hazardous byproduct 2-phospho-glycolate, the enzyme is catalytically flawed. Depending on the climate and the kind of photosynthesis used, the metabolic pathway of photorespiration detoxifies it for carrying out photosynthesis in an O₂-containing atmosphere, which can result in a yield penalty of 20% to 50% [36]. Enhancing Rubisco's activity has been a viable goal to boost agricultural output. Increasing the enzyme's carboxylation capacity is one way to boost Rubisco activity [37]. For example, promoting photosynthesis at high temperatures by the introduction of Rubisco activase from thermophilic cyanobacteria into highly temperature-sensitive plants has demonstrated encouraging results in increasing agricultural productivity [38]. Another strategy is to genetically modify Rubisco to either improve its carboxylase activity or reduce its oxygenation rates.

Furthermore, cyanobacteria's carboxysomes enable them to concentrate carbon dioxide, which aids Rubisco in using it for quicker carbon fixation [39]. Although crop plants do not contain carboxysomes, attempts have been made to boost photosynthesis and production by engineering the complete carbon-concentrating system from cyanobacteria onto crop plants [39].

Global food production still has to be improved to satisfy the demands of the expanding population and changing consumption habits, even while Rubisco engineering techniques have been successful in increasing crop output. Enhancing plant photoprotection is a viable strategy for raising agricultural productivity.

In order to defend themselves from harm, plants have evolved systems for dispersing excess sunlight. However, these mechanisms may not always adapt quickly enough to changing light conditions, resulting in inferior photosynthetic efficiency [40]. The promise of this strategy has been demonstrated by researchers' discovery that modifying photoprotection and light-harvesting systems can increase rice crop output [41]. Protection from too much sunshine lowers the risk of photooxidative stress and photoinhibition, which can have positive impacts on

yield and growth [42]. In full sunlight, nonphotochemical quenching (NPQ) is a crucial process that aids plants in dissipating potentially harmful excess absorbed light energy. However, NPQ mechanisms are slow to relax after frequent sunshade transitions within crops, which can reduce photosynthetic productivity [43]. Finding genes that can improve the process has been the main focus of efforts to increase photoprotection in crops.

Changing the expression levels of the genes that cause nonphotochemical quenching in plants, including PsbS, has been shown to enhance photoprotection and photosynthetic efficiency [42]. Crop development may proceed more quickly now that faster screening techniques have been established to find genes that might enhance photoprotection in crops [44].

The improvement in yield has been greatly aided by transgenic plants. For instance, one study found that overexpressing the *zmm28* gene increased maize production without having any adverse impacts [34]. According to a different research, under stress, a transgenic wheat line outperformed its control by 6% in yield and 9.4% in water usage efficiency [45]. In general, biotechnology methods can enhance agricultural productivity by increasing plant photosynthesis, nutrient uptake, and usage efficiency.

3.2. Nutrient use efficiency

The production outputs in relation to inputs or the recovery of input nutrients is known as nutrient usage efficiency, or NUE. The yield of grain in relation to the total quantity of nitrogen (N) available to the crop from all sources, such as fertiliser, soil organic matter mineralisation, and atmospheric deposition, is known as the NUE. The plant's photosynthetic efficiency is one of the many variables that affect NUE. Because it will lower fertiliser input, increase yield, and minimise environmental losses, maximising NUE is essential for sustainable agriculture. From the standpoint of air and water quality as well as climate change, environmental losses are a concern, particularly for nutrients like nitrogen. Modulating plant nutrient absorption, allocation, and metabolism or optimising root architecture are two ways to use biotechnology to improve NUE. The best way to produce better crop types would be to genetically modify important genes that regulate the rate-limiting stages in nutrient absorption and utilisation efficiency. Among the important genes involved in N-metabolisms are ammonium transport (AMT), nitrate transport (NRT), glutamate synthase (GOGAT), and glutamine synthetase (GS). Research has demonstrated that overexpressing these genes in transgenic crops can boost tissue nitrogen levels, amino acids, biomass, and seed production. The research [46] provides a more thorough explanation of the subjects. Beyond NUE, research is being done to significantly improve the plant's ability to fix its own nitrogen from the environment and synchronise the plant's supply and demand for nitrogen. N fertilisation has a major

impact on cereal crop productivity. In order to create N₂-fixing cereal crops and an alternative to synthetic N fertilisation, biotechnological approaches include (i) engineering the symbiotic relationship between cereals and N₂-fixing bacteria to mimic the legume-rhizobium relationship; (ii) improving the N₂ fixing ability of naturally occurring endophytes of the cereals; and (iii) directly transferring the bacterial nif genes into cereals [47].

3.3. Biotic and abiotic stress resistance

3.3.1. Insect resistance.

Virus resistance. Controlling viral illnesses is still a major concern for the agricultural system, and they continue to be the biggest danger to contemporary agriculture. Conventional management techniques depend on eliminating viral vectors and eliminating sick plants, however they frequently have poor success rates. The production of viral coat protein (RNA-mediated resistance), homology-dependent gene silencing, and microRNA-mediated resistance are examples of biotechnological techniques that have been developed to create plants with resistance to viral infections [51]. The "Rainbow Papaya" is a successful example of a horticulture crop that has been genetically modified to be resistant to viruses. For farmers in Hawaii, USA, who experienced severe production losses as a result of the PRSV, this crop was revolutionary. For farmers who had been waiting patiently for a solution, the creation of the Rainbow Papaya was a beacon of hope [52].

Abiotic stress tolerance. One important aspect of the natural plant habitat is abiotic stress. Plant metabolism, growth, and development can be negatively impacted by abiotic stressors as drought, flooding, waterlogging, high temperatures (cold, chilling, frost, and heat), salt, mineral deficiencies, and toxicity. In severe situations, these variables can potentially kill the plant. These stresses have the potential to reduce output and result in financial losses [53]. Extreme abiotic stressors impact 70% of agricultural productivity globally [54]. However, a number of abiotic stress-tolerant plant types have been created thanks to biotechnological techniques such tissue culture, marker-assisted selection, in vitro mutagenesis, and genetic transformation [55]. The development of various model plants, including *Arabidopsis thaliana*, *Medicago truncatula*, and *Lotus japonicus*, and the advent of "omics" technology in recent years have sparked intriguing approaches to comprehending the molecular and genetic underpinnings of stress tolerance. Bottlenecks in the development of resistant crop types can be removed by understanding the molecular underpinnings of stress resistance [56].

3.4. Herbicide resistance

Weeds pose a persistent problem in agricultural settings, impeding crop growth and development by competing for vital resources such as water, nutrients, sunlight, and space. Moreover, weeds serve as vectors for various insects and pathogenic microorganisms. Unrestrained weed growth can cause significant crop yield reduction, prompting farmers to resort to methods such as herbicide use, tilling, and manual weeding to manage their proliferation. However, these methods have been associated with issues such as groundwater contamination and environmental damage, resulting in a decline of various plant and animal species [57,58]. Biotechnological advancements have led to the development of herbicide-resistant crop varieties such as glyphosate- and glufosinate-tolerant crops [59]. Glyphosate herbicides hinder plant growth by blocking the EPSPS enzyme (5-enolpyruvylshikimate-3-phosphate synthase), which is essential to produce aromatic amino acids, vitamins, and other plant metabolites. Plants engineered with genes such as CP4-EPSP synthase and GOX (glyphosate oxidoreductase) produce glyphosate-tolerant EPSPS and glyphosate-degrading enzymes, respectively [60,61]. Glufosinate herbicides contain the active ingredient phosphinothricin, which inhibits the glutamine synthetase enzyme that plays a key role in nitrogen metabolism. Glufosinate-resistant crops are developed by inserting genes that encode phosphinothricin acetyltransferase (PAT), which

The production of insect-resistant transgenic plants has been a remarkable achievement in agricultural biotechnology, with both public and private sector institutions conducting extensive research in this area. The most widely commercialized transgenic plant contains cry genes from the *Bacillus thuringiensis* bacterium [48,49], but other genes, including API (arrowhead proteinase inhibitor), OC-I (cysteine proteinase inhibitor):

oryzacystatin-I), Vgb (Vitreoscilla hemoglobin), SacB (levansucrase-encoding gene), JERF-36 (Jasmonic ethylene responsive factor), BADH (betadine aldehyde dehydrogenase gene), and NTHK1 (Nicotiana tabacum histidine kinase -1), have also been expressed in various crop varieties [50]. In particular, cotton (*Gossypium hirsutum*) and maize (*Zea mays*) transgenic plants have demonstrated resistance to lepidopteran and coleopteran larvae (caterpillars and rootworms), leading to significant reductions in pesticide usage and production costs while improving crop yields.

detoxifies the glufosinate ammonium by acetylation, thus allowing glutamine synthetase to function unimpeded

Biofortification

Malnutrition is a major issue in many poor nations, especially in Asia, where thousands of children die each year from a lack of access to a healthy food. An exciting prospective answer is the process of biofortification, which raises the macronutrient and micronutrient levels of crops using biotechnology or traditional breeding techniques [63]. In contrast to biotechnological procedures, conventional breeding techniques are time-consuming and have a poor success rate. Malnutrition may be more effectively addressed by the cultivation of genetically modified crops like Golden Rice [64]. In regions like South and Southeast Asia, where rice makes up more than two-thirds of a person's daily caloric intake, golden rice has the potential to be used as a dietary supplement since it can biosynthesize beta-carotene, a precursor to vitamin A [63,65]. Vitamin A-supplemented rice has the potential to significantly reduce the annual death rate from malnutrition, which is now estimated to be 670,000 newborns and young children under the age of five [63,65].

4.0 Conclusions

The agriculture sector has undergone a transformation thanks to biotechnology, which also offers several advantages to both farmers and consumers. It entails the manipulation of living things to develop novel goods, procedures, and methods to deal with a range of agricultural issues. The creation of better crop varieties that are resilient to biotic and abiotic stressors and well suited to various environments is one of the most important effects of biotechnology on agriculture. As a consequence, customers may have a more plentiful and reasonably priced food supply, while farmers can produce more crops with less resources. Although biotechnology has many advantages in agriculture, there are worries about its hazards. Regulations are therefore necessary to keep up with the quick developments in biotechnology. To guarantee the ethical and safe application of these new technologies, the existing infrastructure must evolve appropriately.

References

Frederick AL, Frederick R. FOOD, AGRICULTURE, CONSERVATION, AND TRADE ACT OF 1990: AN OVERVIEW Part II -The Conservation Provisions (Title XIV). 1991.

- Heard PL, Allen AW, Best LB, Brady SJ, Burger W, Esser AJ, et al. A comprehensive review of Farm Bill contributions to wildlife conservation, 1985–2000. Technical Report. 2000.
- Rigby D, Woodhouse P, Young T, Burton M. Constructing a farm level indicator of sustainable agricultural practice. *Ecol Econ*. 2001; 39:463–478. [https://doi.org/10.1016/S0921-8009\(01\)00245-2](https://doi.org/10.1016/S0921-8009(01)00245-2)
- Hefferon KL. Nutritionally Enhanced Food Crops; Progress and Perspectives. *Int J Mol Sci*. 2015; 16:3895–3914. <https://doi.org/10.3390/ijms16023895> PMID: 25679450
- Duke SO, Scheffler BE, Boyette CD, Lydon J, Oliva A. Herbicides, Biotechnology. Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Ltd; 2004. <https://doi.org/10.1002/0471238961.herbduke.a01>
- Dill GM. Glyphosate-resistant crops: history, status and future. *Pest Manag Sci*. 2005; 61:219–224. <https://doi.org/10.1002/ps.1008> PMID: 15662720
- Khush GS, Lee S, Cho J-I, Jeon J-S. Biofortification of crops for reducing malnutrition. *Plant Biotechnol Rep*. 2012; 6:195–202. <https://doi.org/10.1007/s11816-012-0216-5>
- Ray DK, Mueller ND, West PC, Foley JA. Yield Trends Are Insufficient to Double Global Crop Production by 2050. *PLoS ONE*. 2013; 8:e6428. <https://doi.org/10.1371/journal.pone.0066428> PMID: 23840465
- Sumberg J, Giller KE. What is ‘conventional’ agriculture? *Glob Food Sec*. 2022; 32:100617. <https://doi.org/10.1016/j.gfs.2022.100617>
- Schaller N. The concept of agricultural sustainability. *Agriculture and the Environment*. Elsevier; 1993. p. 89–97. <https://doi.org/10.1016/B978-0-444-89800-5.50010-5>
- Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, et al. Solutions for a cultivated planet. *Nature*. 2011; 478:337–342. <https://doi.org/10.1038/nature10452> PMID: 21993620
- Pimentel D, Burgess M. Soil Erosion Threatens Food Production. *Agriculture*. 2013; 3:443–463. <https://doi.org/10.3390/agriculture3030443>
- Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci*. 2011; 108:20260–20264. <https://doi.org/10.1073/pnas.1116437108> PMID: 22106295
- Horrigan L, Lawrence RS, Walker P. How sustainable agriculture can address the environmental and human health harms of industrial agriculture. *Environ Health Perspect*. 2002; 110:445–456. <https://doi.org/10.1289/ehp.02110445> PMID: 12003747
- Altieri MA. Agroecology: the science of natural resource management for poor farmers in marginal environments. *Agr Ecosyst Environ*. 2002; 93:1–24. [https://doi.org/10.1016/S0167-8809\(02\)00085-3](https://doi.org/10.1016/S0167-8809(02)00085-3)
- Kremen C, Miles A. Ecosystem Services in Biologically Diversified versus Conventional Farming Systems: Benefits, Externalities, and Trade-Offs. *Ecol Soc*. 2012; 17. Available from: <https://www.jstor.org/stable/26269237>.
- Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, et al. Food Security: The Challenge of Feeding 9 Billion People. *Science*. 2010; 327:812–818. <https://doi.org/10.1126/science.1185383> PMID: 20110467
- Pannell DJ, Glenn NA. A framework for the economic evaluation and selection of sustainability indicators in agriculture. *Ecol Econ*. 2000; 33:135–149. [https://doi.org/10.1016/S0921-8009\(99\)00134-2](https://doi.org/10.1016/S0921-8009(99)00134-2)
- Allen P, Van Dusen D, Lundy J, Gliessman S. Integrating social, environmental, and economic issues in sustainable agriculture. *Am J Altern Agric*. 1991; 6:34. <https://doi.org/10.1017/S0889189300003787>
- Marja R, Herzon I, Viik E, Elts J, Mañnd M, Tschamtk T, et al. Environmentally friendly management as an intermediate strategy between organic and conventional agriculture to support biodiversity. *Biol Conserv*. 2014; 178:146–154. <https://doi.org/10.1016/J.BIOCON.2014.08.005>
- Reganold JP, Wachter JM. Organic agriculture in the twenty-first century. *Nature Plants*. 2016; 2:15221. <https://doi.org/10.1038/nplants.2015.221> PMID: 27249193
- Rockstroöm J, Williams J, Daily G, Noble A, Matthews N, Gordon L, et al. Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*. 2017; 46:4–17. <https://doi.org/10.1007/s13280-016-0793-6> PMID: 27405653
- Vågsholm I, Arzoomand NS, Boqvist S. Food Security, Safety, and Sustainability—Getting the Trade-Offs Right. *Front Sustain Food Syst*. 2020;4. Available from: <https://www.frontiersin.org/articles/10.3389/fsufs.2020.00016>.
- Padolina WG. Agricultural Biotechnology: Opportunities and Challenges for the Philippines. 2000.

Barrows G, Sexton S, Zilberman D. Agricultural Biotechnology: The Promise and Prospects of Genetically Modified Crops. *J Econ Perspect.* 2014; 28:99–120. <https://doi.org/10.1257/jep.28.1.99>

Tanksley SD, Young ND, Paterson AH, Bonierbale MW. RFLP Mapping in Plant Breeding: New Tools for an Old Science. *Nat Biotechnol.* 1989; 7:257–264. <https://doi.org/10.1038/nbt0389-257>

Wallace JG, Rodgers-Melnick E, Buckler ES. On the road to breeding 4.0: unraveling the good, the bad, and the boring of crop quantitative genomics. *Annu Rev Genet.* 2018; 52:421–444. <https://doi.org/10.1146/annurev-genet-120116-024846> PMID: 30285496

Thorpe TA. History of plant tissue culture. *Mol Biotechnol.* 2007; 37:169–180. <https://doi.org/10.1007/s12033-007-0031-3> PMID: 17914178
Zuo L, Yang R, Zhen Z, Liu J, Huang L, Yang M. A 5-year field study showed no apparent effect of the Bt transgenic 741 poplar on the arthropod community and soil bacterial diversity. *Sci Rep.* 2018; 8:1956. <https://doi.org/10.1038/s41598-018-20322-3> PMID: 29386632

Azad MAK, Amin L, Sidik NM. Gene Technology for Papaya Ringspot Virus Disease Management. *ScientificWorldJournal.* 2014; 2014:e768038. <https://doi.org/10.1155/2014/768038> PMID: 24757435

Gonsalves C, Lee DR, Gonsalves D. Transgenic Virus-Resistant Papaya: The Hawaiian “Rainbow” was Rapidly Adopted by Farmers and is of Major Importance in Hawaii Today. *APSnet Feature Articles.* 2004. <https://doi.org/10.1094/APSnetFeature-2004-0804>

Parmar N, Singh KH, Sharma D, Singh L, Kumar P, Nanjundan J, et al. Genetic engineering strategies for biotic and abiotic stress tolerance and quality enhancement in horticultural crops: a comprehensive review. *3 Biotech.* 2017; 7:239. <https://doi.org/10.1007/s13205-017-0870-y> PMID: 28702937

De Steur H, Blancquaert D, Strobbe S, Lambert W, Gellynck X, Van Der Straeten D. Status and market potential of transgenic biofortified crops. *Nat Biotechnol.* 2015; 33:25–29. <https://doi.org/10.1038/nbt.3110> PMID: 25574631

Wu J, Lawit SJ, Weers B, Sun J, Mongar N, Van Hemert J, et al. Overexpression of zmm28 increases maize grain yield in the field. *Proc Natl Acad Sci.* 2019; 116:23850–23858. <https://doi.org/10.1073/pnas.1902593116> PMID: 31685622

Wei S, Li X, Lu Z, Zhang H, Ye X, Zhou Y, et al. A transcriptional regulator that boosts grain yields and shortens the growth duration of rice. *Science.* 2022; 377:eabi8455. <https://doi.org/10.1126/science.abi8455> PMID: 35862527

Eisenhut M, Weber APM. Improving crop yield. *Science.* 2019; 363:32–33. <https://doi.org/10.1126/science.aav8979> PMID: 30606834

Iñiguez C, Aguilo´-Nicolau P, Galme´s J. Improving photosynthesis through the enhancement of Rubisco carboxylation capacity. *Biochem Soc Trans.* 2021; 49:2007–2019. <https://doi.org/10.1042/BST20201056> PMID: 34623388

Ogbaga CC, Stepien P, Athar H-U-R, Ashraf M. Engineering Rubisco activase from thermophilic cyanobacteria into high-temperature sensitive plants. *Crit Rev Biotechnol.* 2018; 38:559–572. <https://doi.org/10.1080/07388551.2017.1378998> PMID: 28937283

Hines KM, Chaudhari V, Edgeworth KN, Owens TG, Hanson MR. Absence of carbonic anhydrase in chloroplasts affects C3 plant development but not photosynthesis. *Proc Natl Acad Sci.* 2021; 118: e2107425118. <https://doi.org/10.1073/pnas.2107425118> PMID: 34380739

Kromdijk J, Glowacka K, Leonelli L, Gabilly ST, Iwai M, Niyogi KK, et al. Improving photosynthesis and crop productivity by accelerating recovery from photoprotection. *Science.* 2016; 354:857–861. <https://doi.org/10.1126/science.aai8878> PMID: 27856901

Hubbart S, Smillie IRA, Heatley M, Swarup R, Foo CC, Zhao L, et al. Enhanced thylakoid photoprotection can increase yield and canopy radiation use efficiency in rice. *Commun Biol.* 2018; 1:1–12. <https://doi.org/10.1038/s42003-018-0026-6> PMID: 30271909

Murchie EH, Ali A, Herman T. Photoprotection as a Trait for Rice Yield Improvement: Status and Prospects. *Rice.* 2015; 8:31. <https://doi.org/10.1186/s12284-015-0065-2> PMID: 26424004

De Souza AP, Burgess SJ, Doran L, Hansen J, Manukyan L, Maryn N, et al. Soybean photosynthesis and crop yield are improved by accelerating recovery from photoprotection. *Science.* 2022; 377:851–854. <https://doi.org/10.1126/science.adc9831> PMID: 35981033

Gotarkar D, Doran L, Burns M, Hinkle A, Kromdijk J, Burgess SJ. High-Throughput Analysis of Non-Photochemical Quenching in Crops Using Pulse Amplitude Modulated Chlorophyll Fluorometry. *J Vis Exp.* 2022:e63485. <https://doi.org/10.3791/63485> PMID: 35876527

González FG, Capella M, Ribichich KF, Curín F, Giacomelli JJ, Ayala F, et al. Field-grown transgenic wheat expressing the sunflower gene HaHB4 significantly outyields the wild type. *J Exp Bot.* 2019; 70:1669–1681. <https://doi.org/10.1093/jxb/erz037> PMID: 30726944

Beatty PH, Good AG. Improving Nitrogen Use Efficient in Crop Plants Using Biotechnology Approaches. In: Shrawat A, Zayed A, Lightfoot DA, editors. *Engineering Nitrogen Utilization in Crop Plants.* Cham: Springer International Publishing; 2018. p. 15–35. https://doi.org/10.1007/978-3-319-92958-3_2

- Curatti L, Rubio LM. Challenges to develop nitrogen-fixing cereals by direct nif-gene transfer. *Plant Sci.* 2014; 225:130–137. <https://doi.org/10.1016/j.plantsci.2014.06.003> PMID: 25017168
- Tabashnik BE, Brévault T, Carrière Y. Insect resistance to Bt crops: lessons from the first billion acres. *Nat Biotechnol.* 2013; 31:510–521. <https://doi.org/10.1038/nbt.2597> PMID: 23752438
- Tabashnik BE, Gassmann AJ, Crowder DW, Carrière Y. Insect resistance to Bt crops: evidence versus theory. *Nat Biotechnol.* 2008; 26:199–202. <https://doi.org/10.1038/nbt1382> PMID: 18259177
- Wang G, Dong Y, Liu X, Yao G, Yu X, Yang M. The Current Status and Development of Insect-Resistant Genetically Engineered Poplar in China. *Front Plant Sci.* 2018;9. Available from: <https://www.frontiersin.org/article/https://doi.org/10.3389/fpls.2018.01408> PMID: 30298085
- Wilson TM. Strategies to protect crop plants against viruses: pathogen-derived resistance blossoms. *Proc Natl Acad Sci U S A.* 1993; 90:3134–3141. <https://doi.org/10.1073/pnas.90.8.3134> PMID: 8475051
- Gonsalves D. Control of papaya ringspot virus in papaya: a case study. *Annu Rev Phytopathol.* 1998; 36:415–437. <https://doi.org/10.1146/annurev.phyto.36.1.415> PMID: 15012507
- Atkinson NJ, Urwin PE. The interaction of plant biotic and abiotic stresses: from genes to the field. *J Exp Bot.* 2012; 63:3523–3543. <https://doi.org/10.1093/jxb/ers100> PMID: 22467407
- Cramer GR, Urano K, Delrot S, Pezzotti M, Shinozaki K. Effects of abiotic stress on plants: a systems biology perspective. *BMC Plant Biol.* 2011; 11:163. <https://doi.org/10.1186/1471-2229-11-163> PMID: 22094046
- Babar MM, Zaidi N-SS, Azooz MM, Kazi AG. Biotechnology approaches to overcome biotic and abiotic stress constraints in legumes. *Legumes under Environmental Stress.* Chichester, UK: John Wiley & Sons, Ltd; 2015. p. 247–264. <https://doi.org/10.1002/9781118917091.ch15>
- Dita MA, Rispaill N, Prats E, Rubiales D, Singh KB. Biotechnology approaches to overcome biotic and abiotic stress constraints in legumes. *Euphytica.* 2006; 147:1–24. <https://doi.org/10.1007/s10681-006-6156-9>
- Powles SB. *Herbicide Resistance In Plants: Biology And Biochemistry.* CRC Press; 2018.
- Mazur BJ, Falco SC. The Development of Herbicide Resistant Crops. *Annu Rev Plant Physiol Plant Mol Biol.* 1989; 40:441–470. <https://doi.org/10.1146/annurev.pp.40.060189.002301>
- Tan S, Evans R, Singh B. Herbicidal inhibitors of amino acid biosynthesis and herbicide-tolerant crops. *Amino Acids.* 2006; 30:195–204. <https://doi.org/10.1007/s00726-005-0254-1> PMID: 16547651
- Shaner DL. The impact of glyphosate-tolerant crops on the use of other herbicides and on resistance management. *Pest Manag Sci.* 2000; 56:320–326. [https://doi.org/10.1002/\(SICI\)1526-4998\(200004\)56:4<320::AID-PS125>3.0.CO;2-B](https://doi.org/10.1002/(SICI)1526-4998(200004)56:4<320::AID-PS125>3.0.CO;2-B)
- Owen MD, Zelaya IA. Herbicide-resistant crops and weed resistance to herbicides. *Pest Manag Sci.* 2005; 61:301–311. <https://doi.org/10.1002/ps.1015> PMID: 15668920
- Carbonari CA, Latorre DO, Gomes GLGC, Velini ED, Owens DK, Pan Z, et al. Resistance to glufosinate is proportional to phosphinothricin acetyltransferase expression and activity in LibertyLink® and Wide-Strike® cotton. *Planta.* 2016; 243:925–933. <https://doi.org/10.1007/s00425-015-2457-3> PMID: 26733464
- Bouis HE, Hotz C, McClafferty B, Meenakshi JV, Pfeiffer WH. Biofortification: A New Tool to Reduce Micronutrient Malnutrition. *Food Nutr Bull.* 2011; 32:S31–S40. <https://doi.org/10.1177/15648265110321S105> PMID: 21717916
- Ye X, Al-Babili S, Klopfli A, Zhang J, Lucca P, Beyer P, et al. Engineering the provitamin A (beta-carotene) biosynthetic pathway into (carotenoid-free) rice endosperm. *Science (New York, NY).* 2000; 287:303–305.
- Black RE, Allen LH, Bhutta ZA, Caulfield LE, de Onis M, Ezzati M, et al. Maternal and child undernutrition: global and regional exposures and health consequences. *Lancet (London, England).* 2008; 371:243–260. [https://doi.org/10.1016/S0140-6736\(07\)61690-0](https://doi.org/10.1016/S0140-6736(07)61690-0) PMID: 18207566