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REVIEW

Role of biotechnology in creating sustainable agriculture

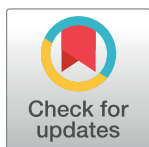
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Abstract

This narrative review paper discusses the role of biotechnology in the development of sustainable agriculture. The paper begins by defining sustainability and highlights the importance of biotechnology in establishing sustainable agriculture. Sustainable agriculture is an approach that prioritizes meeting current food and fiber production needs while conserving and enhancing natural resources for future generations. To achieve agricultural sustainability, it is necessary to strike a balance between economic viability, environmental stewardship, and social responsibility. This can be difficult, especially in the face of biotic and abiotic stresses such as pests, diseases, climate change, soil degradation, and water depletion. The prevalence of pests and diseases that can significantly diminish crop yields and quality is one of the greatest obstacles to sustainable agriculture. Biotechnology can be used to create crops that are resistant to pests and diseases to address these issues. Soil nutrient deficiency is another obstacle to sustainable agriculture, as it can reduce crop yields and plant health. Biotechnology has the potential to play a significant role in developing more productive and nutritious crops. However, at the same time, it is essential to ensure that these technologies are developed in a responsible manner and that their benefits are distributed equitably across communities and regions.



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1.0. Introduction

Sustainable agriculture aims to meet the food and fiber demands of society in an environmentally sound manner that does not harm the natural ecosystem or processes. The integration of a healthy environment and economic profitability with social and economic equality is essential to develop sustainable climate-resilient agriculture. Biotechnology has emerged as a promising tool in crop improvement, offering the potential to increase yield, biotic and abiotic resistance, and nutrient-rich crops.

The term “sustainable” derives from “sustain,” which means to maintain, uphold, and endure. Sustainable agricultural development attempts to meet society’s food and fiber demands with long-term solutions for current and future generations. The primary requirement for sustainable agriculture is to merge a healthy environment and economic profitability

with social and economic equality and to develop climate-resilient agriculture. To attain this goal, sustainable agricultural scientists must use multidisciplinary approaches that combine biology, engineering, chemistry, economics, and community development. The 1990 Farm Bill (The Food, Agriculture, Conservation, and Trade (FACT) Act of 1990) defines sustainable agriculture as an integrated system of plant and animal production practices having a site-specific application that will, over the long term, fulfill the (a) food and fiber needs; (b) enhance environmental quality by judicious use of natural resources; (c) make the most efficient use of on-farm resources by integrating regenerative approaches; (d) improve farm economics; and (e) enhance the quality of life for farmers and society as a whole [1–3].

Biotechnology is the technological application in biology, primarily involving the transfer of genetic material containing a specific trait from one crop/organism to another in order to improve crop productivity and resistance to various biotic and abiotic stresses. Many on-farm and small-plot research studies demonstrated that biotechnological intervention could improve crop yield and nutrient quality [4], and weed management [5] without affecting the ecosystem and environment. Engineered crops like glyphosate-resistant crops make weed control simple and more efficient [6]. The crop can be engineered for disease resistance properties and can decrease the use of synthetic pesticides. Crops can be biofortified by introducing genes specific to certain metabolic pathways, such as Golden Rice fortified by introducing genes for the biosynthesis of beta-carotene [7]. Recent advances in OMICS approaches, especially CRISPR genome editing, have provided more opportunities and hope for developing the second/third generation of biotechnological products. Despite the potential of biotechnology in sustainable agriculture, it still faces challenges due to public sentiments. There is a need for more outreach and extension to answer people's queries and concerns. The potential risks of genetically modified organisms and the need to safeguard biodiversity pose a challenge to the broad applicability of biotechnology in agriculture.

The agricultural revolution in the 21st century is the cumulative effect of improved agromanagement, plant breeding, fertilizer technology, and farm mechanization, which has dramatically improved crop production. However, climate change, abiotic and biotic stress, biodiversity losses, and soil degradation will potentially affect crop production, as studies have described yield stagnation and increased yield variability in recent years. In a study by Ray and colleagues [8] for 4 major crops of the world, maize, rice, wheat, and soybean, the yield of these crops increased by 1.6%, 1.0%, 0.9%, and 1.3% per year, respectively, which is less than the 2.4% per year required rate to meet the demand of the increasing population. The projected world population will reach 9 billion figures by 2030, and the earth will be warmer as we reach 2030; biotechnology will be critical in countering climate change and food security issues.

Biotechnology is a promising tool for improving soil health and nutrient cycling in sustainable agriculture. Microorganisms with specific properties can be added to soil to promote plant growth, suppress plant pathogens, and enhance soil structure and fertility. Biofertilizers and biopesticides are examples of utilizing natural resources to enhance soil health, plant health, and productivity. Biotechnology has vast potential in sustainable agriculture, providing several opportunities to enhance agricultural productivity, quality, and sustainability.

2.0. Conventional versus sustainable agriculture

Understanding the conventional and sustainable agricultural systems, their limitations, and their benefits is crucial before discussing the potential role of biotechnology in enhancing agricultural productivity. The definition and significance of conventional agriculture have undergone a transformation over the years, from traditional farm practices to current intensive

modern agricultural practices [9]. In modern times, conventional agriculture practices entail the use of agrochemicals to maximize production, intensive tillage without crop rotations, and farming practices without organic input. The conventional agricultural system is associated with the production of maximum food and fiber to meet current demand, with little emphasis on environmental quality and ecosystem services. The conventional agriculture system is often referred to as the production system of the industrial era, mostly based on neoclassical economics of supply and demand.

Agriculture faces numerous challenges, primarily climate change and various forms of environmental degradation, such as soil degradation, and abiotic and biotic stresses. To address these challenges, several strategies and farming practices are promoted, and sustainable agriculture emphasizes stewardship and conservation of soil, environment, and ecosystem. Sustainable agriculture encompasses farming practices that are environmentally sound, productive, economically viable, and socially desirable. Nevertheless, it is challenging to define the concept of sustainability as it embodies a way of thinking and farming practices. There are 2 different views on sustainable agriculture. One view advocates for the modification of current conventional agriculture to more efficient and careful farming practices by incorporating technologies that reduce the adverse effects of conventional farming. The other view advocates for the need for fundamental changes in agriculture, transforming agriculture by adding societal values [10].

On a broader perspective, conventional and sustainable agriculture illustrates 2 contrasting paradigms within the agricultural landscape. The former, characterized by a drive towards yield maximization and financial gain, predominantly relies on the use of advanced technologies and synthetic inputs. On the other hand, sustainable agriculture advocates for a balanced ecological approach, emphasizing the preservation and enhancement of soil health, water quality, and biodiversity, alongside optimized yields [11]. Environmental repercussions form a major point of differentiation between these 2 agricultural practices. Owing to its inherent resource intensiveness, conventional agriculture often produces contamination through nutrient losses and loss of soil structure, which is responsible for soil degradation, erosion, air, and water contamination [12,13]. In contrast, sustainable agriculture fosters the conservation and amelioration of natural resources fundamental to farming operations, adopting methods such as organic farming, crop rotation, conservation tillage, and natural fertilizer application [14].

Economic implications further distinguish these farming methodologies. Conventional farming practices typically emphasize immediate financial returns and the use of mechanization, which may catalyze yield increases but also invoke considerable costs, thereby increasing the risk of farmer indebtedness. In comparison, sustainable agriculture can curtail costs by advocating for the efficient use of natural resources and prioritizing soil health enhancement, ultimately fostering augmented long-term yields and profitability [15].

Sustainable agriculture places a premium on the preservation and enhancement of biodiversity, acknowledging its critical role in maintaining robust ecosystems and the long-term sustainability of agricultural practices [16]. Sustainable agriculture emphasizes techniques such as crop rotation, cover cropping, intercropping, and the utilization of natural predators for pest management. While conventional agriculture may frequently produce larger crop quantities, it does so at considerable environmental expense and raises questions about the long-term feasibility of such practices [13]. In contrast, sustainable agriculture endeavors to preserve and enhance the natural resources integral to farming, promote biodiversity, and assure long-term economic viability for farmers.

The primary goal of sustainable agriculture is to cultivate and sustain conditions that allow for the productive coexistence of humanity and nature, supporting present and future generations. Achieving this requires an understanding of the mechanisms underpinning natural

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

3.0. 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.

3.1. Economic sustainability

In the context, “economically sustainable” means that agricultural practices should be economically viable and generate sufficient income for farmers or those involved in food production and processing, to support their livelihoods. Economic sustainability is a primary need to ensure access to good food and life for all people [18,19]. The economic gain will also encourage the wide adoption of sustainable practices. Several key factors can contribute to economic sustainability in agriculture, including:

- a. **Diversification:** Diversifying the types of crops or livestock produced can help to reduce the risk of losses due to weather events, market fluctuations, or disease outbreaks.
- b. **Efficiency:** Implementing efficient farming practices, such as precision agriculture and conservation tillage, can help to reduce costs and increase profitability.
- c. **Resource management:** Sustainable agricultural practices, such as water conservation and soil management, can help to preserve natural resources and improve long-term productivity.
- d. **Market access:** Access to local, regional, and international markets can help promote the economic sustainability of agricultural systems by providing farmers with various options for selling their products.
- e. **Supportive policies and institutions:** Governments and other organizations can promote economic sustainability in agriculture by supporting research and development, providing access to credit and other financial services, and implementing policies that support sustainable practices.

3.2. Environmentally safe and sound

Agriculture should preserve the quality of natural resources that human life, farms, and the surrounding environment rely on, including soil, water, and air. Cooperating with natural resource systems instead of quelling them can benefit food production and conserve the natural environment [20,21]. Several key factors contribute to environmental sustainability in agriculture, including:

- a. **Soil health:** Sustainable farming practices, such as conservation tillage and cover cropping, can help to preserve soil health and prevent erosion.
- b. **Water conservation:** Irrigation techniques, such as drip and precision irrigation, can help reduce water usage and minimize water waste.
- c. **Biodiversity:** Promoting biodiversity on agricultural land through practices such as agroforestry and habitat conservation can help to support a wide range of plant and animal species.
- d. **Pesticide and fertilizer use:** Minimizing the use of synthetic pesticides and fertilizers can help reduce pollution and protect natural resources.

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

3.3. Societal values: Good for families and communities

Agriculture should promote opportunities and cooperative relationships among farmers' families and community members. For example, a local food marketing system in community-supported agriculture offers opportunities for people to get into farming without significant capital investment, provides work for family members on the farm, and creates direct corporations with consumers in the community [22]. Agricultural sustainability can provide a range of societal values, including economic, social, cultural, and environmental benefits.

- a. Economic benefits: A sustainable agricultural sector can generate jobs, create wealth, and stimulate economic growth.
- b. Social benefits: Sustainable agriculture can provide social benefits by supporting rural communities and preserving cultural traditions associated with farming. It can also promote food security and improve access to nutritious food, positively impacting public health.
- c. Cultural benefits: Agriculture can be an essential part of a community's cultural identity, and sustainable agriculture practices can help to preserve and promote these cultural traditions.
- d. Environmental benefits: Sustainable agriculture practices can help to protect natural resources, such as soil and water, and reduce negative environmental impacts, such as pollution and greenhouse gas emissions. This can have short-term and long-term benefits for the environment and the people who depend on it.

3.4. Food and fiber security

Sustainable agriculture must also be secure and sufficient to feed the increasing population. Sufficient food production, source reduction, redistribution, and recycling will be critical in creating a sustainable and secure food system [23]. Agricultural sustainability can contribute to food security in several ways:

- a. Increasing productivity: Sustainable farming practices, such as precision agriculture and conservation tillage with residue management, can help to increase the productivity of agricultural lands, which can lead to a greater supply of food.
- b. Reducing waste: Implementing efficient farming practices and reducing food waste along the supply chain can help increase food availability.
- c. Protecting natural resources: Soil and water conservation can help to preserve natural resources and support long-term food production.
- d. Improving resilience: Sustainable agriculture can be more resilient to external challenges, such as droughts or pests, which can help ensure the food supply's stability.

4.0 Application of biotechnology for sustainable agriculture

The continuing increase in the world's population, coupled with the limitations in the supply of natural resources, loss of usable lands, climate change, and widespread degradation of the environment, presents a significant challenge to agricultural scientists today. Biotechnology will provide alternative methods to current approaches to improve the environment and

agricultural system [24]. Biotechnology can reduce fertilizer and pesticide application in the current agricultural production system. Reduced application of inorganic pesticides and fertilizers can improve soil, air, and water quality. Biotechnology can be an effective strategic approach to developing different high-yielding and stress-tolerant crop varieties [25].

Recent advancements in biotechnology research have primarily focused on elucidating the underlying molecular mechanisms of diverse metabolic processes and applying this knowledge towards improving crop and animal yield. Genetic engineering offers a more precise and quicker method of gene transfer than conventional crossbreeding. By genetic modification, the nutritional profile of crops can be improved, and herbicide, pest, and disease-resistant varieties can be produced. Abiotic stress is a critical hindrance to agricultural productivity, and plants possessing stress tolerance characteristics such as drought, cold, and salinity tolerance can allow farmers to utilize previously unusable land. Genetic mapping can effectively screen for essential traits that are otherwise difficult to trace using conventional breeding, thereby facilitating advanced plant breeding techniques [26,27]. Micropropagation offers the potential to generate multiple copies of cultivars within a short period, leading to faster breeding of improved varieties and serving the germplasm conservation [28].

Agricultural biotechnology involves the application of scientific tools and techniques such as genetic engineering, molecular biology, and micropropagation to modify plants, animals, and microorganisms. Agricultural biotechnology has the potential to provide the solution for major challenges in creating sustainable agriculture, such as growing enough food in provided limited space (loss of usable lands) and with limited resources (water scarcity) under different environmental stress (drought, salinity, high temperature) and using less synthetic fertilizer and pesticides. Ongoing research in biotechnology is expected to bring forth many more types of crops with varied uses in agriculture. For centuries, farmers have employed selective breeding to manipulate plants and animals with desirable traits. The recent surge in biotechnology has enabled the development of molecular tools to identify crucial traits such as increased yield, pest resistance, drought resistance, and herbicide resistance, which can be subsequently modified in crops for the desired traits (Table 1). Future advancements may enable biotechnology to provide consumers with nutritionally enriched foods that last longer. Biotechnology also holds promise in the production of new medicines through genetically engineered crops (plant-based vaccines and antibodies), leading to a new sustainable plant-made pharmaceutical industry that reduces production costs.

Apart from crop production, biotechnology also holds the potential for soil quality improvement through phytoremediation. Biotechnology can also help conserve natural resources, enhance nutrient utilization by plants, reduce nutrient runoff, increase soil organic carbon sequestration, and meet increasing food and land demands by producing hardier crops that thrive in harsh environments with minimal inputs of fuel, labor, fertilizer, and water. The use of biotechnology in agriculture has enabled the development of 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]

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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.

4.1. Yield improvement

As the world's population continues to grow, improving crop yield will be critical to ensure food security. To achieve this goal, genetic manipulation can be used to enhance major yield-determining traits such as photosynthesis, shoot-to-root biomass, inflorescence architecture, stomatal movement and density regulation, nutrient acquisition and use efficiency, microbial interactions, resistance to environmental stresses such as drought, salinity, flooding, extreme temperature, and resistance to pests and pathogens.

A recent study has demonstrated that overexpression of the gene *OsDREB1C* can significantly increase rice yield by 41.3% to 68.3% compared to the wild types. The efficiency of plants in capturing photosynthetically active solar radiation and converting it into biomass plays a crucial role in determining the yield. The expression of the *OsDREB1C* gene in rice shortened the growth duration improved nitrogen use efficiency and promoted an efficient resource allocation [35].

One of the key factors that determine the photosynthetic efficiency of a plant is Rubisco. Rubisco is a crucial enzyme for photosynthesis as it assimilates atmospheric CO₂ into biomass and is a major driver of the global carbon cycle. However, the enzyme is catalytically imperfect, as it accepts both CO₂ and O₂ as substrates, which creates a toxic by-product, 2-phosphoglycolate. The metabolic pathway of photorespiration detoxifies it for performing photosynthesis in O₂ containing atmosphere, which can cost a yield penalty of 20% to 50% depending on the environmental conditions and the type of photosynthesis employed [36]. Improving the activity of Rubisco has been a promising target to increase crop production. One approach to improve Rubisco activity is to enhance the carboxylation capacity of the enzyme [37]. For instance, engineering Rubisco activase from thermophilic cyanobacteria into high temperature-sensitive plants has shown promising results in enhancing crop yield by improving photosynthesis under elevated temperatures [38]. Another approach is to increase Rubisco's carboxylase activity or decrease its oxygenation rates through genetic engineering of the enzyme. In addition, carboxysomes in cyanobacteria allow them to concentrate carbon dioxide, which helps Rubisco use it for a faster carbon fixation [39]. While crop plants lack carboxysomes, efforts have been made to engineer the entire carbon-concentrating mechanism from cyanobacteria into crop plants to improve their photosynthesis and yield [39]. Despite the success in boosting crop yield through Rubisco engineering methods, global food production still needs to be increased to meet the demands of the growing population and dynamic consumption patterns.

Improving photoprotection in plants is a promising approach for increasing crop yield. Plants have developed mechanisms for dissipating excess sunlight to protect themselves from damage, but these mechanisms do not always adjust rapidly enough to changing light conditions, leading to suboptimal photosynthetic efficiency [40]. Researchers have found that altering photoprotection and light-harvesting processes can improve yield in rice crops, demonstrating the potential of this approach [41]. Protection from excess sunlight reduces the likelihood of photoinhibition and photooxidative stress, which can have beneficial effects on

growth and yield [42]. Nonphotochemical quenching (NPQ) is an essential process that helps plants dissipate potentially damaging excess absorbed light energy in full sunlight, but NPQ mechanisms are slow to relax following the frequent sunshade transitions that occur within crops, which can limit photosynthetic productivity [43]. Efforts to improve photoprotection in crops have focused on identifying genes that can enhance the process. Researchers have studied the genes responsible for nonphotochemical quenching in plants, such as PsbS, and have found that altering their expression levels can improve photoprotection and photosynthetic efficiency [42]. Faster screening methods have been developed to identify genes that can improve photoprotection in crops, which could speed up the process of crop improvement [44].

Transgenic plants have significantly contributed to yield improvement. For example, one study showed that overexpression of the *zmm28* gene resulted in greater maize yield without any negative effects [34]. Another study found that a transgenic wheat line had a 6% higher yield and 9.4% greater water use efficiency compared to its control under stress conditions [45]. Overall biotechnological approaches can help in improving plant photosynthesis, nutrient acquisition, and use efficiency to improve crop yield.

4.2. Nutrient use efficiency

Nutrient use efficiency (NUE) is defined as the production outputs relative to inputs or in terms of recovery of input nutrients. For nitrogen (N), the NUE is defined as the yield of grain relative to the amount of N available to the crop from all the sources, including fertilizer, mineralization of the organic matter in the soil, and atmospheric deposition. NUE is dependent on several factors including the photosynthetic efficiency of the plant. Maximization of NUE is critical for sustainable agriculture, as it will reduce fertilizer input, improve yield, and reduce environmental losses. Environmental losses, especially for nutrients like nitrogen, are a concern from the perspective of water and air quality and climate change. One approach to improving NUE using biotechnology is to modulate plant nutrient absorption, allocation, and metabolism or optimize root architecture. Genetic manipulation of key genes controlling the rate-limiting steps in nutrient uptake and utilization efficiency would be an ideal approach to creating improved crop varieties. Ammonium transport (AMT), nitrate transport (NRT), glutamine synthetase (GS), and glutamate synthase (GOGAT) are some of the key genes responsible for N-metabolisms. Studies have shown transgenic crops with overexpression of these genes can increase the tissue N levels, amino acids, biomass, and seed numbers. A more detailed discussion on the topics can be found in the study [46]. Beyond NUE, there are studies that are involved in vastly improving the plant to fix its own N from the atmosphere and synchronizing the plant N demand with plant N supply. The productivity of cereal crops is highly dependent on N fertilization. Biotechnological approaches include (i) engineering the symbiotic relationship between cereals and N₂-fixing bacteria to mimic the legume-rhizobium relationship; (ii) enhancing of N₂ fixing ability of naturally occurring endophytes of the cereals; and (iii) direct transfer of the bacterial *nif* genes into cereals have been envisioned to develop N₂-fixing cereal crops and an alternate approach to synthetic N fertilization [47].

4.3. Biotic and abiotic stress resistance

4.3.1. Insect resistance. 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.

4.3.2. Virus resistance. Viral diseases continue to pose the greatest threat to modern agriculture and controlling them remains a significant challenge for the agricultural system. Traditional management methods rely on eradicating viral vectors and destroying infected plants, but success rates are often low. Biotechnological approaches have been developed to engineer plants with resistance to viral pathogens, including the expression of viral coat protein (RNA-mediated resistance), homology-dependent gene silencing, and microRNA-mediated resistance [51]. One successful example of genetically engineered horticultural crops with viral resistance is the “Rainbow Papaya.” This crop was a game changer for farmers in Hawaii, USA, who suffered significant losses in production due to the PRSV. The development of the Rainbow Papaya was a ray of hope for farmers, who had been patiently waiting for a solution [52].

4.3.3. Abiotic stress tolerance. Abiotic stress is a significant factor in the natural plant environment. Abiotic stress factors such as drought, flooding, waterlogging, extreme temperatures (cold, chilling, frost, and heat), salinity, mineral deficiency, and toxicity can adversely affect plant metabolism, growth, and development, and in extreme cases, even cause the death of the plant. These stressors can limit productivity and cause economic losses [53]. Worldwide 70% of crop production is affected by extreme abiotic stresses [54]. However, biotechnological tools such as marker-assisted selection, tissue culture, in vitro mutagenesis, and genetic transformation have led to the development of several abiotic stress-tolerant plant varieties [55]. In recent years, the emergence of “omics” technologies and the establishment of several model plants, such as *Arabidopsis thaliana*, *Medicago truncatula*, and *Lotus japonicus*, have initiated promising strategies for understanding the molecular and genetic basis of stress resistance. Knowledge of the molecular basis of stress resistance can remove bottlenecks in developing resistant crop varieties [56].

4.4. 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

detoxifies the glufosinate ammonium by acetylation, thus allowing glutamine synthetase to function unimpeded [62].

4.5. Biofortification

Malnutrition is still a significant problem in many developing countries, particularly in Asia, where thousands of children lose their lives every year as a result of a lack of access to balanced diets. The process of biofortification, which increases the micronutrient and macronutrient values of crops through conventional breeding or biotechnological methods, is an encouraging potential solution [63]. Conventional breeding methods require a lot of time and have a low success rate in comparison to biotechnological approaches. The production of genetically modified crops, such as Golden Rice, has the potential to address the issue of malnutrition in a more efficient manner [64]. Golden Rice is capable of biosynthesizing beta-carotene, which is a precursor to vitamin A, and has the potential to serve as a nutrient supplement in areas such as South and Southeast Asia, where rice accounts for more than two-thirds of an individual's daily calorie intake [63,65]. Rice that has been supplemented with vitamin A could significantly cut the death rate associated with malnutrition, which currently stands at an estimated 670,000 infants and young children under the age of 5 per year [63,65].

5.0. Conclusions

Biotechnology has revolutionized the agricultural industry and provided a plethora of benefits to farmers and consumers alike. It involves the manipulation of living organisms to create new products, processes, and techniques to address various challenges in agriculture. One of the most significant impacts of biotechnology on agriculture is the development of improved crop varieties resistant to biotic and abiotic stresses, making them well adapted to different environments. As a result, farmers can produce more crops with fewer resources, and consumers can have a more abundant and affordable food supply. Despite the numerous benefits of biotechnology in agriculture, there are also concerns about the potential risks associated with this technology. As such, there is a need for regulatory policies to keep pace with the rapid advancements in biotechnology. The current infrastructure must develop accordingly to ensure the safe and responsible use of these new technologies.

Author Contributions

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