Review Article

Application and recent trends of biotechnology in sustainable agriculture: A brief review

Abstract

India has emerged as one of the world's fastest growing economies. Although agriculture and other sectors employ about 52% of the Indian population, the majority of farmers still rely on subsistence farming with average annual incomes below poverty levels. Despite the fact that we have achieved food self-sufficiency following the green revolution, the condition of small and marginal farmers remains unchanged. Climate change, biotic and abiotic pressures, tiny landholdings, land degradation, low market prices for products, and a lack of low input-high output technologies are the key difficulties we must address in order to boost farmer income. The use of innovative technologies is one of the most effective strategies for raising crop output and farmer revenue. Biotechnology is one of the most appealing crop improvement methods, and it is the most rapidly adopted technology worldwide. Plant tissue culture, molecular breeding, transgenic development, and animal cloning are all key methods in biotechnology. It has improved yield, tolerance to stress, quality, and introduced new features, such as bio-plastic manufacturing. Biotechnology in agriculture has increased farmer income and agricultural sustainability in both developed and developing countries. It has multiple applications, including crop development, livestock enhancement, and fisheries. To improve farmers' lifestyles and the status of Indian agriculture while preserving international standards of food quality and nutritional value, it is vital to promote the use of biotechnology in agriculture and related fields.The article opens by defining sustainability and emphasizing the critical role of biotechnology in achieving sustainable agriculture. Sustainable agriculture aims to produce adequate food and fiber to satisfy current needs while safeguarding and enhancing natural resources for future generations.

Keywords: Agricultural biotechnology, crop and pests resistance, genetically modified crops

Introduction

Food security has become a significant concern due to global population growth, particularly in developing countries, which necessitates a 70% increase in food production by 2050. This highlights the urgency of enhancing agricultural productivity in the coming decades (Chekol and Gebreyohannes, 2018). Biotechnology plays a pivotal role in this effort, focusing on developing methods to boost crop production. It involves the application of scientific techniques to modify and improve plants, animals, and microbes, enhancing their value. Genetic engineering, a branch of biotechnology, offers substantial potential benefits when applied responsibly and ethically. To ensure informed decision-making, society must have a thorough understanding of the principles of biotechnology and genetic engineering, including the techniques for creating transgenic organisms, the types of genetic material utilized, and the associated advantages and risks of these technologies.Agricultural biotechnology is the field of biotechnology that applies to agriculture. Modern biotechnology introduces innovative scientific applications that benefit society by developing crops with improved nutritional value, resistance to pests and diseases, and reduced production costs. In agriculture, biotechnology has emerged as a transformative tool, revolutionizing food production and enhancing crop yields. It is also reshaping animal feeding practices to improve nutrition and minimize environmental waste (James, 2002). While agricultural biotechnology holds significant potential to benefit the poor (Tanaka *et al*., 2010), it is also extensively utilized for disease diagnosis and the development of animal vaccines. Additionally, cereal starch plays a crucial role in producing value-added biopolymers and biofuels, offering environmentally friendly alternatives to petrochemicals (Thitisaksakul*et al.*, 2012; Kumar *et al*., 2020).

The term "sustainable" originates from the verb "sustain," meaning to maintain, uphold, or endure. Sustainable agriculture aims to meet society's food and fiber needs while safeguarding the environment and supporting natural processes.To create sustainable, climate-resilient agriculture, social and economic equality must be combined with economic prosperity 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. Developing climate-resilient agriculture and combining social and economic equality with a healthy environment and financial success are the main prerequisites for sustainable agriculture. Economic profitability, environmental stewardship, and social responsibility must all be balanced in order to achieve agricultural sustainability. Particularly when dealing with biotic and abiotic stresses including pests, diseases, climate change, soil erosion, and water scarcity, this can be challenging. These problems can be solved by using biotechnology to produce crops that are resistant to diseases and pests. Lack of nutrients in the soil can lower agricultural production and plant health, which is another barrier to sustainable agriculture. More productive and nutrient-dense crops could be developed with the help of biotechnology. At the same time, though, it is crucial to make sure that new technologies are developed responsibly and that regions and people equally benefit from them. This article summarizes biotechnology's multiple applications in agriculture, highlighting its significant contributions to crop development, pest and disease management, and sustainable farming practices (Das *et al.,* 2023).

Historical background of agricultural biotechnology

Biotechnology has its origins in ancient times, when people started modifying biological systems for useful purposes. Around 10,000 years ago, early farmers domesticated plants and animals by selecting breeding them for desired qualities like improved flavor and larger yields. This set the stage for current plant breeding. By establishing the laws of inheritance through his studies with pea plants, he discovered the concepts of heredity, which became the scientific foundation for biotechnology. Advanced breeding methods were made possible by this genetic foundation (Smykal *et al.,* 2016). The production of food and beverages advanced as a result of Louis Pasteur's work on fermentation, which revealed the microbiological underpinning of this process (Katz, 2012). The 1928 discovery of penicillin transformed medicine and demonstrated the biotechnological potential of microbes (Kingston, 2000). When molecular biology emerged in the middle of the 20^{th} century, the structure of DNA was discovered, laying the groundwork for genetic engineering. Genetically modified organisms (GMOs) were made possible by the advancement of recombinant DNA technology in the 1970s, revolutionizing agricultural science. The term "genetically modified organism" or "GMO" is commonly used, however genetic manipulation has been practiced for centuries. Crossing one variety with alternative results in offspring that are genetically modified relative to their parents. Foods developed from transgenic plants are referred to as "GMO foods," "GMPs" (genetically modified products), or "biotech foods." Genetically engineered foods might be referred to as "biotechnology-enhanced foods" or "frankenfoods" (Wieczorek, 2003).

Agriculture's Biotechnology Evolution

Developments in genetics, molecular biology, and plant breeding methods have propelled a substantial evolution in biotechnology in agriculture. Mendelian genetics improved conventional plant breeding techniques, resulting in hybrid crops that showed better resistance to pests and diseases and had larger yields. The introduction of high-yielding rice and wheat varieties during the Green Revolution greatly increased food production and prevented famines in emerging nations (Shiferaw *et al.,* 2013). Direct manipulation of plant genomes became possible with the introduction of genetic engineering in the 1970s and 1980s. Early in the 1980s, tobacco and petunia were among the first plants to be genetically modified. The commercialization of genetically modified crops began in the 1990s, with the FlavrSavr tomato bred for longer shelf life, followed by herbicide-resistant soybeans and insect-resistant Bt cotton, both of which soon gained popularity due to their agronomic benefits. The introduction of CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats)-Cas9 gene editing technology in the early twenty-first century transformed agricultural biotechnology by allowing for precise genome editing, which improved features such as nutritional content, pest resistance, and tolerance to environmental stress. Modern plant breeding approaches, such as marker-assisted selection (MAS) and genomic selection, use molecular markers to discover and select desired features, resulting in faster crop development and improved breeding efficiency. Tissue culture and micro-propagation techniques enable rapid replication of disease-free planting material while conserving genetic resources (Tegen and Mohammed, 2016).

Milestones in Indian Agricultural Biotechnology

India has a long history of agricultural innovation, and it was an early adopter of agricultural biotechnology. The creation of the Indian Agricultural Research Institute was a key milestone, as it developed and disseminated high-yielding wheat and rice varieties during the Green Revolution (Zeigler and Mohanty, 2010). Another significant milestone was the commercialization of Bt cotton in 2002, when it became the first GM crop in India. Bt cotton, resistant to the bollworm insect, enhanced yields, reduced pesticide use, and raised farmer profitability. By 2018, it covered over 90% of the cotton-growing area. While Bt cotton has been successful, other GM crops, such as Bt brinjal and GM mustard, have suffered regulatory and popular acceptance issues. Bt brinjal has not been commercialized because to biosafety issues and public opposition, while GM mustard has been pending approval since 2016. India has made great advances in biotechnology, including increasing the use of bio-fertilizers and insecticides to improve soil fertility and reduce chemical inputs. The National Organic Farming Project promotes the use of bio-fertilizers and organic farming practices. The Indian Council of Agricultural Research (ICAR) has created superior crop varieties using MAS and genomic selection, thereby speeding up the breeding process and increasing attributes such as yield and disease resistance (Chakraborti *et al.,* 2021). The Department of Biotechnology (DBT), as well as institutes such as the National Agri-Food Biotechnology Institute (NABI) and the Biotechnology Industry Research Assistance Council (BIRAC), have bolstered India's agricultural biotechnology research and innovation capabilities. Recent research focuses on using CRISPR-Cas9 technology to improve crop features such as disease resistance and nutritional value. In India, the Genetic Engineering Appraisal Committee (GEAC) oversees agricultural biotechnology regulations, assuring the safety of genetically modified crops through risk assessments, field experiments, and public participation. Public opinion and acceptance, regulatory barriers, and approval process delays are all significant challenges. Addressing these needs efficient communication, transparent regulatory processes, and rigorous biosafety assessments (Cornish *et al.,* 2021, Kumar *et al.,* 2024).

Advancements in Agricultural Biotechnology

Genetically modified (GM) crops are a groundbreaking advancement in agricultural science. Crops are developed with specific features that improve growth, yield, and resilience. This approach involves incorporating genes from various species into the target crop's genome to enhance traits like pest resistance, herbicide tolerance, and nutritional value. The first genetically modified crops were introduced in the mid-1990s, and their acceptance has since risen tremendously around the world. Soybean, maize, cotton, and canola are the most frequently produced genetically modified crops, with features such as herbicide tolerance and insect resistance built in. Herbicide-tolerant crops, such as Roundup Ready soybeans and maize, enable farmers to control weeds more effectively while minimizing crop damage, resulting in better weed management methods and reduced tillage, which enhances soil health.*Bacillus thuringiensis* genes are found in insect-resistant crops like Bt cotton and Bt maize. These crops produce proteins that are harmful to particular insect pests, lowering the need for chemical insecticides and safeguarding beneficial insect populations. The safety of genetically modified crops for human consumption and the environment is guaranteed by extensive study and regulatory inspection; multiple studies have confirmed that GM crops are just as safe as their conventional counterparts and provide environmental benefits like decreased greenhouse gas emissions and pesticide use.Bt cotton adoption has resulted in significant production gains and reduced pesticide use. According to studies, Bt cotton growers achieve 30-60% higher yields than non-Bt cotton farmers, with a 40-70% reduction in insecticide applications. Smallholder farmers saw a 24% rise in cotton income as a result of these benefits, leading to higher profitability and improved rural livelihoods. Despite the success of Bt cotton, commercialization of other GM crops in India, like as Bt brinjal and GM mustard, has experienced regulatory and public acceptability problems due to biosafety concerns and opposition. Building trust in genetically modified (GM) technology involves transparent and science-based regulatory systems, as well as effective communication with stakeholders (Kumar *et al.,* 2024).

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology is a ground breaking genetic engineering tool that enables precise genome editing (Loureiro and Silva, 2019). The CRISPR-Cas9 system, derived from bacterial immunity, employs a guide RNA to direct the Cas9 enzyme to a specific DNA sequence, resulting in the addition, removal, or change of genetic material. This approach has advantages over traditional genetic editing procedures, including increased precision, efficiency, and versatility. CRISPR can be used to create crop types with better features such as increased yield, higher nutritional content, resistance to pests and diseases, and tolerance to environmental challenges (Jaganathan *et al.*, 2018). CRISPR technology has great potential for Indian agriculture, addressing issues such as food security, climate change, and sustainability. CRISPR has been utilized by Indian researchers to generate disease-resistant agricultural varieties, such as tomato plants resistant to the tomato yellow leaf curl virus, as well as rice and wheat with improved fungal disease resistance. CRISPR technology is being utilized to enhance agricultural nutrition, including bio-fortified rice with added iron and zinc to treat micronutrient inadequacies (Kumar *et al.*, 2019). Investing in research and capacity building for scientists and farmers is crucial for realizing CRISPR's potential in improving Indian agriculture (Munawar *et al.*, 2024).

Marker-assisted selection (MAS) is a molecular breeding technique that utilizes DNA markers to identify and select plants with anticipated traits early in the breeding process. It is widely employed to develop crop varieties with increased yields, enhanced resistance to diseases and pests, and improved tolerance to abiotic stresses such as drought and salinity. In India, MAS has been used to create multiple high-yielding and disease-resistant crop types, including rice cultivars resistant to bacterial blight and blast, as well as wheat varieties immune to rust disease. MAS has also been used to boost the nutritional value of crops, such as bio-fortified pearl millet with high amounts of iron and zinc, so treating micronutrient inadequacies (Srivastava, *et al.,* 2021). Genomic selection (GS) is an advanced molecular breeding strategy that utilizes genome-wide markers to predict breeding line performance. GS uses high-density markers distributed across the genome to estimate breeding value. This enables for more precise selection of plants with complex properties regulated by numerous genes, such as yield, drought tolerance, and disease resistance. In India, GS has been used on major crops including as rice, wheat, and maize. Collaborative work with institutes such as the International Rice Research Institute have employed GS to generate high-yielding rice cultivars that are more resilient to environmental challenges (Pathak *et al.,* 2018).

Bio-fertilizers and bio-pesticides are crucial components of sustainable agriculture, providing ecologically benign alternatives to chemical fertilizers and insecticides. Bio-fertilizers use microorganisms to improve plant nutrient availability, whereas bio-pesticides use natural materials such as plants, bacteria, and minerals to promote soil health, reduce pollution, and increase crop yields (Kawalekar, 2013). Bio-fertilizers such as Rhizobium, Azotobacter, Azospirillum, and phosphate-solubilizing bacteria (PSB) are frequently utilized in diverse cropping systems to improve nitrogen availability and phosphorus nutrition. Bio-pesticides, such as neem-based solutions and *Bacillus thuringiensis* (Bt) formulations, successfully manage a variety of pests while lowering the need for chemical pesticides. Bio-fertilizers boost nutrient availability and uptake, resulting in better plant growth and yields. Rhizobium inoculants can boost nitrogen fixation and yields by 20-30%, whereas PSB enhances phosphorus availability and crop yields. Bio-pesticides help to achieve sustainable pest management by reducing the demand for chemical pesticides, lowering environmental impact, and increasing yields (Khan *et al,* 2022).

Biotechnology application for sustainable agriculture

Agricultural biotechnology is a key toolset that scientists use to study and modify the genetic makeup of organisms for applications in crops, forestry, fisheries, and livestock. Techniques such as micro-propagation, tissue culture, cloning, artificial insemination, embryo transfer, markers-assisted selection, genomics and bioinformatics, and other technologies are all part of the broad range of applications that biotechnology offers beyond genetic engineering. Scientists can use a variety of methods in modern agricultural biotechnology to comprehend and modify an organism's genetic composition for use in the production or processing of agricultural products. Problems in every aspect of agriculture production and processing are being solved by biotechnology.

Today's agricultural scientists face several challenges, including the world's population growth, the depletion of natural resources, and the loss of arable land, climate change, and environmental degradation. Biotechnology will offer alternatives to existing strategies for enhancing the agricultural system and environment. Biotechnology has the potential to decrease the use of pesticides and fertilizers in the current agricultural production system. The quality of the soil, air, and water can be enhanced by using fewer inorganic fertilizers and pesticides. Biotechnology can be an effective strategic approach to developing different high-yielding and stress-tolerant crop varieties. The main goal of recent developments in biotechnology research has been to clarify the molecular principles underlying various metabolic processes and use this understanding to increase crop and animal productivity. Gene transfer by genetic engineering is faster and more accurate than traditional crossbreeding. Herbicide, pest, and disease-resistant crop varieties can be created by genetic alteration, which can also improve the nutritional profile of crops. Agricultural productivity is severely hampered by abiotic stress, and farmers can make use of previously unsuitable land by cultivating plants with stress tolerance traits including resistance to cold, drought, and salinity. The use of scientific instruments and methods, including genetic engineering, molecular biology, and micro-propagation, to alter plants, animals, and microbes is known as agricultural biotechnology. The development of sustainable agriculture may be aided by agricultural biotechnology in addressing key issues like producing enough food in a limited amount of space (loss of usable lands), with limited resources (water scarcity), under various environmental stresses (high temperatures, salinity, and drought), and with fewer synthetic fertilizers and pesticides.

Biotechnology also has the ability to improve soil quality through phytoremediation, in addition to crop production. By creating hardier crops that can survive in challenging conditions with little fuel, labour, fertilizer, or water input, biotechnology can also help conserve natural resources, improve plant nutrient uptake, decrease nutrient runoff, increase soil organic carbon sequestration, and satisfy rising food and land demands. Crops resistant to severe illnesses have been developed thanks to the application of biotechnology in agriculture. Biotechnology is essential to sustainable agriculture because it makes it possible to create crops with improved qualities like drought tolerance, pest resistance, and nutritional value. This results in higher crop yields, less use of pesticides, and ultimately more financial success for farmers while having a smaller negative impact on the environment. Recent advances in biotechnology have made it possible to create molecular tools that can be used to detect important qualities like higher yield, resistance to pests, drought, and herbicides. These traits can then be modified in crops to achieve the desired outcomes. Das *et al.* (2023) documented various biotic and abiotic stress-resistant crops, including insect-resistant Poplar 741, virus-resistant Rainbow papaya and SunUP papaya, herbicide-tolerant Petunia hybrida (glyphosate-tolerant), drought-tolerant apple, tomato, and potato, salt-tolerant apple and tomato, biofortified rice, maize, and potato, and high-yielding maize. Additionally, biotechnology offers significant potential for developing novel medicines using genetically modified crops, such as plant-based vaccines and antibodies, paving the way for a sustainable plant-based pharmaceutical industry with reduced production costs.

1. **Impact on Agricultural Productivity**

Yield improvements

The use of agricultural biotechnology has resulted in significant yield increases across a variety of crops. Transgenic crops with improved photosynthetic efficiency, lower height, greater harvest index, and better nutrient utilization can increase agricultural output potential. New genome technology and bioinformatics tools will transform Indian agriculture, improving photosynthetic efficiency and agricultural yields.A significant example is India's adoption of genetically modified (GM) Bt cotton. *Bacillus thuringiensis*-derived genes in Bt cotton produce proteins that are poisonous to specific insect pests. Since its launch in 2002, it has been widely accepted by Indian farmers. Numerous studies have shown that Bt cotton producers can increase their yields by 30% to 60% when compared to non-Bt cotton farmers. Controlling the bollworm pest has greatly reduced crop damage, leading to increased yields. A study studied data from 1,500 cotton farmers in four main cotton-growing states in India and found that adopting Bt cotton resulted in a 24% increase in yields and 50% increase in revenues. Aside from cotton, other GM crops, such as GM maize, have seen considerable yield improvements. A meta-analysis of 76 research on GM maize revealed a 25% increase in yield compared to conventional maize. GM crops provide much higher yields compared to traditional farming practices that use conventional breeding and chemicals (Kumar *et al.*, 2024). Pesticide reduction also has environmental benefits, such as lowering the chemical load on ecosystems and encouraging beneficial insect populations (Boudh and Singh, 2019). Similarly, GM maize with insect resistance and herbicide tolerance addresses pest infestation and weed competition, resulting in higher and more stable yields, demonstrating biotechnology's potential to overcome key limitations of traditional farming and contribute to sustainable agricultural productivity. Recent studies have demonstrated the significant impact of genetic modification on crop yields. Overexpressing the gene OsDREB1C in rice increased production by 41.3% to 68.3% compared to wild types (Wei *et al*., 2022). Transgenic plants have substantially contributed to yield improvements. For instance, overexpression of the zmm28 gene boosted maize production without adverse effects (Wu *et al*., 2019). Similarly, a transgenic wheat line showed a 6% higher yield and a 9.4% improvement in water use efficiency under stress conditions compared to its control (González *et al*., 2019).

Nutrient use efficiency improvement

Nutrient use efficiency (NUE) refers to the ratio of production outputs to inputs or the rate at which input nutrients are utilized by crops. For nitrogen (N), NUE is defined as the grain yield relative to the total nitrogen available from sources such as fertilizers, soil organic matter mineralization, and atmospheric deposition. NUE is influenced by several factors, including the plant's photosynthetic efficiency. Enhancing NUE is vital for sustainable agriculture, as it minimizes fertilizer use, boosts crop output, and reduces environmental losses. These losses, particularly of nitrogen, raise concerns about water and air quality and their impact on climate change. Genetic modification of key genes controlling rate-limiting processes in nutrient uptake and utilization efficiency offers a promising approach for developing superior crop varieties. Key genes involved in N metabolism include those encoding glutamine synthetase, glutamate synthase, nitrate transporters, and ammonium transporters (Das *et al.*, 2023). Recently, Wei *et al*. (2022) demonstrated that overexpressing the *OsDREB1C* gene in rice significantly improved production compared to wild types. The expression of *OsDREB1C* shortened growth duration, increased NUE, and promoted efficient resource allocation.

2. **Impact on biotic and abiotic stress resistance/climate resilience**

Insect resistance

Both public and commercial sector institutions have made significant strides in developing insect-resistant transgenic plants, marking a major achievement in agricultural biotechnology. The most widely commercialized transgenic plants incorporate cry genes from the Bacillus thuringiensis bacterium (Tabashnik et al., 2008, 2013). However, other genes have also been explored, such as API (arrowhead proteinase inhibitor), OC-I (oryzacystatin-I, a cysteine proteinase inhibitor), Vgb (Vitreoscillahemoglobin), SacB (levansucrase-encoding gene), JERF-36 (Jasmonic ethylene responsive factor), BADH (betaine aldehyde dehydrogenase gene), and NTHK1 (Wand et al., 2018).Transgenic cotton and maize plants have shown resistance to lepidopteran and coleopteran larvae, resulting in lower pesticide costs and increased crop yields. According to studies, Bt cotton growers use between 40% and 70% less insecticide than non-Bt cotton farmers. This cuts production costs while also reducing farmers' and agricultural workers' exposure to dangerous chemicals. Reduced pesticide use benefits the environment by reducing chemical runoff, soil contamination, and dangers to non-target creatures such as beneficial insects and mammals. Bt cotton's success in reducing pesticide use has sparked interest in developing other GM crops with similar pest resistance traits. Bt brinjal, while not yet commercialized in India, has shown effectiveness in controlling the fruit and shoot borer pest, potentially reducing the need for chemical insecticides in brinjal cultivation.

Disease resistance

The Indian Council of Agricultural Research has created various rice cultivars that are resistant to major diseases like bacterial blight and blast. Rice variety IR64, selected for resistance to bacterial blight through marker-assisted selection, has much reduced disease incidence and higher yields than susceptible varieties. Wheat, maize, and pulse crops have benefited from biotechnological interventions, with resistant varieties reducing disease and pest yield losses and leading to enhanced production (Pathak *et al.*, 2018).

Controlling viral infections is a major concern in modern agriculture. Traditional management strategies aim to eradicate viral vectors and sick plants, but have low success rates. Plants can be engineered with viral resistance using biotechnological methods such as RNA-mediated expression, homology-dependent gene silencing, and microRNA-mediated resistance (Wilson, 1993). The University of Hawaii and Cornell University, reported successful example, generated two types of papaya by transmitting a virus gene to papaya plants that are resistant to papaya ring spot virus by transferring one of the virus' genes to papaya. Since 1998, papaya growers have received seeds from the two kinds, known as 'SunUp' and 'Rainbow', under licensing arrangements (Gonsalves, 1998).

Abiotic stress tolerance/climate resilience impact and sustainability

Climate change poses significant challenges to agricultural productivity, particularly in regions affected by drought and water scarcity. Plants in their natural environments are subjected to various abiotic stresses, including drought, flooding, waterlogging, extreme temperatures (cold, chilling, frost, and heat), salinity, mineral deficiencies, and toxicity, all of which can negatively impact plant metabolism, growth, and development, potentially leading to plant mortality. These stresses can reduce productivity and cause substantial economic losses, with extreme abiotic conditions affecting 70% of global agricultural output. However, biotechnological advancements, including marker-assisted selection (MAS), tissue culture, in vitro mutagenesis, and genetic transformation, have led to the development of several abiotic stress-tolerant plant cultivars. The introduction of "omics" technologies and the use of model plants like *Arabidopsis thaliana, Medicago truncatula,* and *Lotus japonicus* have opened up promising avenues for studying the molecular and genetic foundations of stress tolerance (Das et al., 2023). For instance, the drought-tolerant rice variety SahbhagiDhan, developed through marker-assisted selection, performs better under drought conditions than traditional varieties (Majumder et al., 2023). Similarly, drought-tolerant maize varieties have been created through both conventional breeding and genetic engineering. Flood-tolerant rice varieties, such as Swarna-Sub1, developed by the International Rice Research Institute (IRRI) in collaboration with Indian research institutions, contain the Sub1 gene, which provides resistance to submergence for up to two weeks (Mackill et al., 2012).Flood-tolerant rice cultivars, such as Samba Mahsuri-Sub1 and CR1009-Sub1, have been adopted in India's flood-prone regions, assisting farmers in mitigating flooding impacts and sustaining production (Dar, *et al.*, 2018).

Soil Health and Fertility

Biotechnology is an exciting tool for enhancing soil health and nutrient cycling in sustainable agriculture. Microorganisms with certain qualities can be introduced into soil to boost plant development, control plant diseases, and improve soil structure and fertility. Bio-fertilizers and bio-pesticides are two examples of using natural resources to improve soil health, plant health, and productivity. Bio-fertilizers, such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi, improve soil fertility and reduce the need for chemical fertilizers, which can harm soil over time. Rhizobium inoculants in leguminous crops fix atmospheric nitrogen, increasing soil nitrogen levels without the negative environmental impact of synthetic fertilizers. Genetically engineered cover crops can enhance soil health by reducing erosion, increasing organic matter, and improving structure. Long-term research on the impact of biotechnology on soil quality have yielded varied results, requiring careful management and monitoring. A meta-analysis indicated that GM crops, particularly Bt crops, led to improved soil microbial diversity and activity by reducing pesticide use (Belousova, *et al.*, 2021). Biotechnology has enormous potential for sustainable agriculture, offering numerous chances to improve agricultural output, quality, and sustainability.

Water Use Efficiency

Biotechnology has brought novel ideas for improving water use efficiency in agriculture, hence addressing increasing water constraint. A fundamental goal is to develop drought-tolerant GM crops that can maintain productivity in water-limited settings. These crops have characteristics that promote water intake, minimize transpiration, and increase stress tolerance. For example, GM maize cultivars with enhanced drought tolerance improve root growth, water retention, and cellular stress responses, resulting in greater yields in water-limited situations than conventional varieties. Genetic alterations that improve physiological features like stomatal conductance and photosynthetic efficiency also help to increase water use efficiency. GM rice varieties with altered stomatal density and behaviour improve water efficiency while retaining high photosynthetic rates and yields (Blum, 2009). In India, drought-tolerant rice cultivars such as SahbhagiDhan, which were produced using marker-assisted selection, have had a considerable impact. According to field trials and farmer experiences, SahbhagiDhan retains higher yields and grain quality when exposed to water stress than older varieties.

Ecosystem balance and biodiversity

The relationship between agricultural biotechnology and local biodiversity is complex and disputed. Genetically modified crops raise concerns about effects on non-target organisms, gene flow to wild relatives, and changes in agricultural practices impacting biodiversity. Bt crops, which produce insecticidal proteins, have been shown to reduce pest populations while having negligible effects on non-target organisms. For example, Bt cotton effectively controls bollworm populations without adversely affecting natural predators and pollinators (Tian, *et al.*, 2015). Research indicates that gene flow can occur, but its ecological influence is frequently limited by reproductive barriers and environmental constraints. Minimizing the risk of gene flow and its impact on biodiversity requires effective containment tactics and regulatory measures. Implementing best management methods like integrated pest management (IPM) and crop rotation improves the sustainability of genetically modified crops. IPM uses biological, cultural, and chemical management strategies to successfully manage pests while reducing environmental damage.

1. **Herbicide tolerance and resistance**

Farmers frequently use chemical pesticides to regulate weed development because weeds compete with crops for critical resources such as soil nutrients, water, and sunlight, resulting in lower agricultural yields. Moreover, weeds act as vectors for a variety of insects and dangerous pathogens. Uncontrolled weed growth can significantly reduce agricultural productivity, requiring farmers to use herbicides, tilling, and manual weeding to control their spread. Herbicides are used directly on crops in modern agriculture to suppress weed development. Farmers use mixtures of several herbicides once plants begin to grow since these herbicides typically have selective effects, attacking just specific plants while conserving the crop. To simplify weed control and promote the use of safer chemicals, scientists have looked into genetically engineering crops to be resistant to a wide spectrum of herbicides. This genetic modification has been used in a variety of crops, including corn, soybeans, cotton, canola, sugar beets, rice, and flax, and some of these genetically modified cultivars are marketed in numerous countries.

Herbicide-resistant crop varieties, such as glyphosate and glufosinate-tolerant crops, have been developed as a result of biotechnological developments. Glyphosate herbicides reduce plant development by inhibiting the EPSPS enzyme (5-enolpyruvylshikimate-3-phosphate synthase), which is necessary for the production of aromatic amino acids, vitamins, and other plant metabolites. Plants modified with genes like CP4-EPSP synthase and GOX (glyphosate oxidoreductase) produce glyphosate-tolerant EPSPS and glyphosate-degrading enzymes, respectively (Shaner, 2000 and Owen, 2005).

2. Quality and nutritional value improvement

The quality of agricultural products is the primary factor of their market price. The use of poorer planting material, a lack of nutrients, inadequate storage facilities, and a variety of biotic and abiotic stresses all have a negative impact on crop quality. This ultimately reduces farmers' income. Biotechnology can improve both the quality and nutritional content of agricultural products. Genetic engineering and plant tissue culture have been employed to extend the shelf life and keeping properties of food crops, as well as to enhance their colours and aromas (Matas, 2009).Fruit juices have a short shelf life. Tomatoes are widely consumed globally. Harvest tomatoes in the ripe green stage for transportation. Exposure to ethylene promotes early ripening and subsequent harvesting. Tomatoes ripen faster at higher temperatures, but their flavor may be compromised at lower temps. Calgene, a California-based business, developed genetically modified tomatoes to address the issue. They developed the FlavrSavr tomato variety to address the issue. Polygalacturonase is an enzyme that breaks down pectin to ensure that it ripens properly. Scientists genetically engineered tomatoes to reduce the amount of enzyme. Antisense RNA is utilized for this specific reason (Adenle, 2011).Low levels of the enzyme cause cell wall and pectin breakdown in stronger tomatoes. These FlavrSavr tomatoes have a firmer texture, a longer shelf life, and better transportability (Dawkins B, 2010).

Malnutrition is a major issue in underdeveloped nations, especially in Asia, where thousands of children die each year due to a lack of availability of balanced diets. Bio-fortification, which raises crop micronutrient and macronutrient values by conventional breeding or biotechnology approaches, is a promising prospective option. Crops can be genetically modified to contain more vitamins, hence increasing their nutritional value. Three genes have been added to genetically modify "golden rice," allowing plants to produce beta-carotene, which the human body turns into vitamin A (Ye *et al.,* 2000). Vitamin A insufficiency is the primary cause of blindness in children, affecting up to 250 million of them worldwide. Golden rice can biosynthesize beta-carotene, a precursor to vitamin A. It could be used as a nutrient supplement in South and Southeast Asia, where rice accounts for about two-thirds of daily calorie intake (Black, 2008). Biotechnology has also been used to modify the composition of specific oil crops in order to improve the amount of oil produced or to alter the type of oil produced.Crops with high nutritional quality features, such as iron-rich rice and vitamin A-rich rapeseed oil, as well as the development of edible vaccines and other pharmaceutical proteins, can benefit human and livestock health.

Biotechnology is being used to create more flavourful fruits. GM foods with increased taste include eggplant, cherries, peppers, seedless watermelon, and tomatoes. Removing the seeds from fruits leads to increased sugar content in soluble form, resulting in sweeter fruits (Falk *et al., 200*2). Biotechnology alters fermentation processes to enhance wine flavor and aroma (Haroon and Ghazanfar, 2016).

Utilizing gene-editing methods, biotechnology plays a key role in producing new varieties with distinct colours, scents, sizes, and blooms. Utilizing biotechnological methods such breeding, micro-propagation, tissue culture, mutation, and creation of polyploidy. There are many different kinds of decorative plants. More than 50 ornamental plants are now being changed using particle bombardment and Agrobacterium-mediated transformation techniques.

3. Biofuels development

Future prosperity is heavily reliant on the availability of egalitarian, secure, sustainable, and inexpensive energy. Production of biofuel is one of the emerged trends in recent years. Biotechnology is also being utilized in agriculture for the production of biofuels. Biofuels are fuels made from natural components such as algae, maize stover, and sugarcane bagasse, which reduce dependency on petroleum products. Biofuels are carbon-free and help reduce greenhouse gas emissions.Moreover, biofuel production does not compete with food production because certain inputs, such as algae, can be grown using wastewater or on non-arable land. Expanding fuel sources increases access and competition, potentially lowering prices. Six microalgae strains were photosynthesised in a photobioreactor. The Chlorella vulgaris strain is the most prominent of the six microalgae used in biodiesel production. *Chlorella vulgaris* was used as a feedstock. The quality of biofuel and lipid production could be used as criteria for selecting biodiesel-producing species. Modern biotechnological techniques allow for the development of biofuels, which have the potential to reduce greenhouse gas emissions and provide a more reliable fuel supply (Francisco, 2010).

4. Social and Economic Effects

Agricultural biotechnology improves crop yields and reduces production costs, leading to increased income and profitability for farmers. Bt cotton, resistant to the bollworm pest, minimizes the need for chemical pesticides, resulting in lower input costs and higher net earnings. A meta-analysis found that GM crops boost yields by an average of 21%, leading to increased farmer incomes.Bt cotton has been a success in India, with adoption increasing since 2002 and covering more than 90% of the cotton-growing region by 2018, resulting in a 24% increase in yields and a 50% increase in revenues. Higher and more consistent yields allow farmers to diversify their revenue streams by investing in livestock, secondary crops, or small companies, resulting in a more resilient economic base and less sensitivity to crop failure and market changes. Agricultural biotechnology's economic benefits vary by location in India, reflecting varying agro-climatic conditions and farming techniques. Bt cotton adoption in Maharashtra, a major cotton-growing state, has resulted in increased yields and incomes. According to an IFPRI study, Bt cotton farmers in Maharashtra had an average yield increase of 34%, resulting in an increased income of INR 18,000 per hectare compared to non-Bt cotton producers (Venugopalan and Reddy, 2017). The expansion of the biotechnology sector has been a driver of employment creation, contributing to overall economic development. The biotechnology sector encompasses research and development (R&D), production, processing, and distribution of biotech goods, producing employment in a variety of roles, ranging from highly qualified research scientists to field workers and technicians. The socioeconomic impact of agricultural biotechnology goes beyond individual farmers and into rural development as a whole. Increased profitability of GM crops has led to infrastructural improvements, such as irrigation systems, storage facilities, and transportation networks. Farmers in Maharashtra and

Gujarat have leveraged greater income from Bt cotton to implement modern irrigation methods, resulting in improved crop yield and water efficiency (Birthal, 2013).

Conclusions

Agriculture biotechnology applications help to sustain food production. Biotechnology complements, rather than replaces, many aspects of traditional agricultural research. It offers a range of tools to enhance our understanding and management of genetic resources for food and agriculture. By transforming the agricultural economy, biotechnology has brought numerous benefits to both farmers and consumers. It involves using living organisms to develop new products, methods, and strategies to address agricultural challenges.One of the most notable effects of biotechnology on agriculture, has transformed crop development by creating transgenic crops with improved yield, pest and disease resistance, and environmental tolerance. Genetically modified crops have improved farmer productivity and profitability while reducing the need for chemicals, leading to more sustainable and environmentally friendly farming practices. Biotechnology has the potential to be a game changer in meeting the world's rising food demand while minimizing its negative environmental impact, resulting in a more resilient and sustainable agricultural system.

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