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Shivli Singh
M. Sc., Department of
Horticulture, (Floriculture and
Landscaping), Phagwara, Punjab,
India

Dr. Bolagam Ravikumar
M. Sc., Department of
Horticulture, (Floriculture and
Landscaping), Phagwara, Punjab,
India

Kulbir Singh
M. Sc., Department of
Horticulture, (Floriculture and
Landscaping), Phagwara, Punjab,
India

Corresponding Author:
Shivli Singh
M. Sc., Department of
Horticulture, (Floriculture and
Landscaping), Phagwara, Punjab,
India

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Biotechnology and technological advancements in agriculture: A review

Shivli Singh, Bolagam Ravikumar and Kulbir Singh

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Abstract

Biotechnology has revolutionized agriculture by introducing innovative approaches to enhance crop production, resilience, and sustainability. This review examines the pivotal role of biotechnology in addressing the global challenges of food security and environmental sustainability. Key advancements, including genetic engineering, CRISPR-Cas technology, molecular markers, and microbial biotechnology, have led to the development of high-yield, climate-resilient crops, improving pest resistance, stress tolerance, and nutritional quality. The integration of precision agriculture, synthetic biology, and AI further optimizes agricultural practices, providing targeted solutions for nutrient delivery and pest management. Despite these benefits, challenges such as public perception of GMOs, biosafety concerns, intellectual property issues, and economic barriers persist, hindering widespread adoption. This review also emphasizes the future prospects of biotechnology, with a focus on climate-smart agriculture and sustainable practices. Ultimately, the review highlights the necessity of balancing innovation with sustainability to ensure the responsible development and deployment of biotechnological solutions in agriculture, underscoring the importance of collaboration between governments, researchers, and industry stakeholders.

Keywords: Biotechnology, agricultural advancements, genetic engineering, CRISPR-Cas 9 technology, precision agriculture, GMOs, sustainable agriculture, climate-resilient crops

Introduction

Biotechnology, a multifaceted discipline that bridges natural sciences and engineering, has become a cornerstone of modern innovation (Mosier and Ladisch, 2011) ^[49]. It has transformed multiple domains of human life by leveraging biological systems, organisms, and processes to develop groundbreaking products and services (Udegbe *et al.*, 2024) ^[75]. The term "biotechnology" was first introduced by Károly Ereky in 1919, signifying the production of goods from raw materials using living organisms (Goyal, 2018) ^[26]. Over the years, this field has evolved to include diverse technologies such as genetic engineering, tissue culture, fermentation, and bioinformatics, which are now indispensable across sectors like agriculture, medicine, and environmental science (Hulse, 2004) ^[31]. Biotechnology's journey from a concept to a transformative scientific domain illustrates its vast potential. Initially confined to the use of microorganisms for fermentation and industrial processes, biotechnology now encompasses advanced tools and methods that enable precise manipulation of biological entities at the molecular and cellular levels (Fatima *et al.*, 2024) ^[20]. It plays a pivotal role in addressing contemporary challenges, including food insecurity, healthcare needs, and environmental degradation. The integration of biotechnology into various industries has led to revolutionary breakthroughs, highlighting its adaptability and utility in diverse applications. In the realm of agriculture, biotechnology has emerged as a game-changing technology (Betz *et al.*, 2023) ^[12]. It addresses pressing global challenges such as food security, malnutrition, and environmental sustainability. By integrating advanced genetic tools and techniques, biotechnology has enabled the development of high-yielding, nutrient-rich, and resilient crop varieties (Joshi *et al.*, 2023) ^[33]. Genetic engineering, a hallmark of agricultural biotechnology, allows precise alterations to an organism's DNA, leading to crops with enhanced resistance to pests, diseases, and adverse environmental conditions. For instance, genetically modified (GM) crops, such as pest-resistant cotton and vitamin-A enriched golden rice, have not only improved agricultural productivity but

also contributed to better nutrition and food security globally. The application of molecular markers and marker-assisted selection has revolutionized traditional plant breeding methods. These markers enable the identification and inheritance tracking of desirable traits, thereby increasing the efficiency and precision of breeding programs (Singh and Singh, 2015) ^[67]. This innovation has accelerated the development of improved crop varieties tailored to specific agricultural needs, such as drought tolerance and pest resistance. These advancements have significantly shortened the time required for breeding programs, enabling faster responses to emerging agricultural challenges (Kumar and Walia, 2024) ^[38].

Tissue culture techniques represent another cornerstone of agricultural biotechnology. This method involves the cultivation of plant cells or tissues under sterile conditions to produce disease-free, high-quality plants (Kumar and Walia, 2024) ^[38]. Tissue culture has become an invaluable tool for mass propagation, ensuring uniformity and boosting productivity. It is also instrumental in conserving endangered plant species and preserving genetic diversity, addressing the dual goals of biodiversity conservation and agricultural sustainability (Pithiya *et al.*, 2022) ^[53]. Biotechnology has also promoted sustainable farming practices through the development of eco-friendly inputs like biopesticides and biofertilizers (Priyanka *et al.*, 2021) ^[54]. Unlike conventional chemical-based products, these biological solutions are derived from natural sources, reducing environmental pollution and enhancing soil health. Biopesticides effectively control pests without harming beneficial organisms, while biofertilizers improve nutrient availability in the soil, fostering sustainable agricultural practices (Asghar *et al.*, 2022) ^[8]. Recent advancements in genomics and CRISPR technology have ushered in an era of precision agriculture. CRISPR, a revolutionary genome-editing tool, allows scientists to make specific and targeted modifications to an organism's DNA (Balasubramanian and Karthickumar, 2017) ^[11]. This technology has enabled the creation of climate-resilient crops capable of thriving under challenging conditions such as drought, salinity, and extreme temperatures. By addressing the impacts of climate change on agriculture, these innovations ensure a more stable and secure food supply. Biotechnology's contributions extend beyond productivity enhancements. It provides solutions to mitigate the environmental impact of conventional agricultural practices, reduce reliance on chemical inputs, and develop sustainable farming systems (Kour *et al.*, 2020) ^[35]. Additionally, biotechnology facilitates the production of biodegradable plastics, biofuels, and bioremediation technologies, further emphasizing its role in creating a sustainable future. The advancements in biotechnology have transformed traditional agricultural practices into a more sustainable, productive, and resilient system. By addressing global challenges such as food insecurity, malnutrition, and climate change, biotechnology remains at the forefront of efforts to ensure a secure and sustainable food supply (Abdi *et al.*, 2024) ^[3]. As the field continues to evolve, it promises to shape a future where innovation and sustainability go hand in hand, meeting the demands of a growing global population while preserving the planet's resources. This comprehensive review highlights the pivotal role of biotechnology in agriculture, its recent advancements, and its potential to create a more resilient and sustainable future for humanity (Ervin *et al.*, 2010) ^[19].

Historical Perspective: Evolution of Biotechnology in Agricultural Practices

Biotechnology, though often associated with modern scientific

advancements, has deep historical roots intertwined with the evolution of agriculture. The application of biological systems to create products dates back thousands of years, making agriculture itself one of the earliest examples of biotechnology (Ruane and Sonnino, 2011) ^[59].

Early Beginnings: The Neolithic Revolution and Selective Breeding

The advent of agriculture during the Neolithic Revolution marked humanity's transition from nomadic lifestyles to settled food production systems. Early farmers unknowingly employed rudimentary biotechnology by selecting and breeding crops with desirable traits, such as higher yields or resilience to environmental conditions (Meyer, 2016) ^[48]. This practice laid the foundation for genetic modification, albeit through natural selection and hybridization rather than modern laboratory techniques. As agricultural practices expanded, ancient civilizations discovered that certain organisms and their by-products could enhance productivity. For instance, bacteria in soil contributed to nitrogen fixation, while organic fertilizers improved soil fertility (Ammerman and Cavalli-Sforza, 2014) ^[6]. These early applications of biotechnology enabled humans to support growing populations and establish agrarian societies.

Fermentation: An Ancient Biotechnological Innovation

Fermentation, one of the earliest biotechnological processes, emerged independently in ancient Mesopotamia, Egypt, China, and India. Brewing beer, fermenting soy sauce, and leavening bread were achieved by harnessing microorganisms, such as yeast and bacteria (Taveira *et al.*, 2021) ^[68]. These processes, though not fully understood at the time, transformed raw materials into value-added products, demonstrating the potential of biological systems for human benefit (El-Mansi, 2018) ^[18]. It wasn't until Louis Pasteur's groundbreaking work in the 19th century that the science of fermentation was demystified, marking a significant milestone in biotechnology.

Advances in Selective Breeding and Darwin's Contribution

Selective breeding evolved as a cornerstone of agricultural biotechnology. For centuries, farmers used this technique to enhance crop quality and livestock traits (Ruse, 2002) ^[61]. For example, corn was selectively bred to produce sweeter and larger kernels. Charles Darwin's observations on variation and natural selection further enriched the understanding of selective breeding, providing scientific validation to practices that had been refined over generations (Toro, 2011) ^[70].

The Industrial Era: Biotechnology Takes Shape

The 20th century witnessed a dramatic transformation in biotechnology, fueled by advances in microbiology and biochemistry (Tylecote, 2019) ^[74]. In 1917, Chaim Weizmann utilized pure microbiological cultures to produce acetone from corn starch, demonstrating the industrial potential of biotechnology (Adams, 2017) ^[4]. This discovery not only addressed immediate needs, such as explosive production during World War I, but also showcased the scalability of biological processes. Another landmark was the discovery of penicillin by Alexander Fleming in 1928, followed by its large-scale production for medicinal use (Pulikkottil, 2017) ^[55]. This achievement underscored the capability of microorganisms to produce life-saving compounds, laying the groundwork for modern biopharmaceuticals.

The Modern Era: Genetic Engineering and Beyond

Modern biotechnology as we know it emerged in the 1970s with

the advent of recombinant DNA technology. Pioneering experiments by Paul Berg, Herbert Boyer, and Stanley Cohen demonstrated the potential to manipulate genetic material for specific purposes (Yi, 2008) ^[79]. The legal recognition of genetically modified organisms (GMOs) in 1980, through the landmark *Diamond v. Chakrabarty* case, opened avenues for commercial biotechnology applications (Libengood, 2015) ^[41]. In agriculture, genetic engineering revolutionized crop production, leading to the development of genetically modified seeds resistant to pests, diseases, and environmental stresses. The rise of biofuels, driven by genetically modified corn and soybeans, further exemplified biotechnology's transformative impact on global food and energy systems (Sahu *et al.*, n.d.) ^[62].

Biotechnology in the Digital Age

The integration of biotechnology with engineering and information technology has given rise to bioinformatics and advanced tools like CRISPR-Cas9. These innovations enable precise genetic modifications and have accelerated the development of climate-resilient crops (Hafeez *et al.* 2023) ^[27]. Additionally, biosensors, such as BioFETs and DNAFETs, are revolutionizing agricultural diagnostics by enabling real-time monitoring of soil, water, and crop health.

Objective of this Review

The primary objective of this review is to explore the transformative role and advancements of biotechnology in agriculture. It delves into the evolution of biotechnological applications, from early techniques like selective breeding and fermentation to modern innovations such as genetic engineering, CRISPR-Cas9, and bioinformatics. These advancements have revolutionized agricultural practices, addressing critical challenges like food security, pest management, nutrient enhancement, and environmental sustainability. Additionally, the review evaluates the impact of biotechnology across three key dimensions: productivity, sustainability, and resilience. By enhancing crop yields, improving livestock genetics, and optimizing agricultural efficiency, biotechnology has significantly boosted productivity. It also supports sustainable farming practices by minimizing chemical inputs, enriching soil health, and developing crops suited to low-resource conditions. Moreover, biotechnology strengthens resilience by enabling agricultural systems to adapt to climate change, pests, diseases, and other environmental stresses. Collectively, these aspects highlight biotechnology's indispensable role in ensuring a productive, sustainable, and resilient agricultural future.

Major Applications of Biotechnology in Agriculture Genetic Engineering and GMOs

The development of genetically modified (GM) crops represents a transformative milestone in agricultural biotechnology (Hassan and Abdolkader, 2023) ^[29]. These crops are engineered by altering their genetic material to introduce beneficial traits such as pest resistance, herbicide tolerance, improved nutritional value, and enhanced adaptability to environmental stress. The process begins with identifying desirable traits, such as resistance to pests or tolerance to drought, followed by isolating the genes responsible for these characteristics (Singh *et al.*, 2021) ^[56]. Using advanced techniques like *Agrobacterium*-mediated transformation, gene gun methods, or CRISPR-Cas9 technology, the selected genes are inserted into the target crop's genome. Once the transformation is successful, the modified cells are grown in selective media to ensure that only the cells carrying the new gene survive (Rauf *et al.*, 2016) ^[58]. These cells

are then regenerated into whole plants through tissue culture methods. The resulting GM plants undergo rigorous testing in controlled environments to assess the expression of desired traits and to ensure safety and stability. Subsequently, field trials are conducted to evaluate their performance under natural conditions and to assess potential ecological impacts.

Upon meeting stringent regulatory standards for safety, allergenicity, toxicity, and environmental effects, GM crops are approved for commercial cultivation (Li *et al.*, 2017) ^[40]. Examples include Bt cotton, which produces its own insecticidal proteins, and herbicide-tolerant soybeans and corn, which simplify weed management. Additionally, biofortified crops like Golden Rice address nutritional deficiencies, particularly in regions where rice is a staple food. The widespread adoption of GM crops has significantly increased agricultural productivity, reduced chemical pesticide use, and improved food security (Goodman, 2014) ^[25]. However, their development remains a subject of debate due to concerns about ethics, environmental impact, and socioeconomic implications. Despite these challenges, GM crops continue to play a vital role in addressing global agricultural challenges and ensuring sustainable food production.

India has emerged as a prominent global player in the production, processing, and trade of raw cotton and its finished products, with genetically modified (GM) crops playing a key role in this transformation. A landmark achievement in cotton farming has been the introduction of Bt cotton, which contains the *cry* gene from the soil bacterium *Bacillus thuringiensis* sub-species *kurstaki* (Carvalho, 2006) ^[16]. This genetically modified variety provides inherent resistance against bollworms, one of the most destructive pests in cotton cultivation. The widespread adoption of Bt cotton by Indian farmers within just seven years highlights the transformative power of this technology, revolutionizing cotton farming in the country (Venugopalan *et al.*, 2009) ^[77]. The introduction of the Bt gene has brought significant changes in the morphological, phenological, and physiological characteristics of cotton cultivars (Bilal *et al.*, 2012) ^[14]. These changes have improved pest resistance, enhanced crop yield, and reduced reliance on chemical insecticides (Ganguly *et al.*, 2017) ^[23]. Additionally, the development of Bt cotton varieties like BN Bt, which incorporates herbicide tolerance, is set to further revolutionize cotton farming. However, to ensure the sustainability of Bt cotton's success, it is crucial to standardize sound agro-techniques (Venugopalan *et al.*, 2009) ^[77]. These techniques should optimize the expression of the Cry toxin while maintaining high-quality fiber production. Research on Bt cotton, particularly under India's diverse growing conditions, is ongoing and plays a key role in maximizing its potential (Pardo-López *et al.*, 2013). It is essential to investigate how various agro-techniques influence Cry toxin expression and fiber quality. This research is vital for ensuring that Bt cotton continues to thrive, contributing significantly to India's agricultural landscape and helping farmers achieve sustainable productivity (Venugopalan *et al.*, 2009) ^[77].

Another exemplary genetically modified crop that addresses critical global challenges is Golden Rice, which was developed to combat micronutrient deficiencies, particularly vitamin A deficiency (Lee and Krinsky, 2016) ^[39]. Micronutrients are essential for human health, and because humans cannot produce them, they must obtain them through the food chain. While staple crops, such as rice, are crucial for feeding the global population, they are often deficient in essential micronutrients. Conventional breeding methods often fail to address these

deficiencies due to a lack of genetic variability and the complex genetic makeup of some crops. In these cases, genetic modification offers a more effective solution (Fu, 2015) ^[22].

Golden Rice has been genetically engineered to produce provitamin A (beta-carotene), which the body can convert into vitamin A. This breakthrough in biotechnology demonstrates how genetic engineering can overcome the limitations of conventional breeding, enabling the introduction of vital nutrients into staple crops. Golden Rice holds immense potential in combating vitamin A deficiency, a public health concern in many developing countries where access to diverse sources of micronutrients is limited. The development of Golden Rice exemplifies the power of genetic modification to enhance the nutritional content of staple crops, making them more beneficial for human health (Kowalski, 2015) ^[36]. By incorporating genes that produce essential micronutrients, such as vitamin A, Golden Rice has the potential to improve the health and well-being of millions, especially in regions where micronutrient deficiencies are prevalent. Disregarding genetic modification as a tool for addressing such challenges would undermine efforts to enhance public health and nutrition worldwide. Genetic modification is a powerful tool that can significantly contribute to addressing some of the most pressing nutritional challenges, ensuring a healthier and more sustainable future (Anyshchenko, 2022) ^[7].

Genetically modified (GM) crops, such as Bt Cotton and Golden Rice, have been engineered to improve key traits that enhance agricultural productivity and address global challenges. Bt Cotton, for example, has been modified to contain a gene from the bacterium *Bacillus thuringiensis*, which provides resistance against pests like the cotton bollworm, reducing the need for chemical insecticides and leading to higher yields and lower environmental impact (Zafar *et al.*, 2020) ^[80]. Additionally, certain varieties of GM crops, including Bt Cotton, have been designed with herbicide tolerance, allowing them to survive the application of specific herbicides that control weeds without harming the crop. This trait simplifies weed management and reduces labor and costs associated with manual weeding. Furthermore, genetic modification has also been applied to enhance drought tolerance in crops, improving their ability to withstand water scarcity by boosting water-use efficiency and reducing water loss (Ruggiero *et al.*, 2017) ^[60]. While not the primary trait of Bt Cotton or Golden Rice, ongoing research is focusing on integrating drought tolerance into these crops for greater resilience in dry regions. Golden Rice, in particular, is an example of a GM crop with enhanced nutritional value, as it has been engineered to produce provitamin A (beta-carotene) to address vitamin A deficiency in developing countries. Together, these improved traits pest resistance, herbicide tolerance, and drought tolerance demonstrate the potential of GM crops to enhance agricultural efficiency, sustainability, and food security in the face of global environmental and nutritional challenges.

Molecular Markers and Marker-Assisted Selection

Molecular markers and marker-assisted selection (MAS) have become integral components of modern crop breeding programs, significantly enhancing the efficiency and precision of crop improvement (Jiang, 2013) ^[32]. Molecular markers, which are specific DNA sequences associated with desirable traits, serve as tools to track gene inheritance in crops. These markers enable breeders to identify and select plants with traits such as disease resistance, drought tolerance, and improved yield at an early stage, thereby accelerating the breeding process. Marker-assisted selection improves upon traditional breeding methods by streamlining the identification of plants carrying beneficial

traits. This approach reduces the reliance on phenotypic screening, which can be both time-consuming and costly. MAS enables breeders to select plants based on their genetic makeup, even before these traits are visibly expressed, thereby speeding up the development of improved crop varieties (Mapari and Mehendi, 2024) ^[45]. This technology is especially valuable for complex traits that are governed by multiple genes, such as resistance to diseases and abiotic stress tolerance, facilitating the selection of individuals that carry the desired genetic variations.

Tissue Culture and Micropropagation

Tissue culture and micropropagation have revolutionized plant propagation and play a pivotal role in the conservation of endangered species. These techniques involve the cultivation of plant cells, tissues, or organs under controlled conditions, enabling the rapid production of large numbers of genetically identical plants (Malabadi *et al.*, 2023) ^[43]. This method is especially valuable for the propagation of plants that are difficult to propagate through conventional methods such as seeds or cuttings. In plant propagation, tissue culture offers the advantage of producing uniform, disease-free plants in a relatively short period. It is particularly useful for mass propagation of commercial crops, ornamentals, and plants with desirable traits. Micropropagation, a form of tissue culture, allows for the rapid multiplication of high-quality planting material. This technique is instrumental in improving crop production by ensuring the mass production of healthy plants, which can be crucial for agriculture and horticulture industries. Tissue culture also plays a crucial role in the conservation of endangered plant species (Tripathi *et al.*, 2021) ^[72]. Many plants, especially those at risk of extinction due to habitat destruction, overharvesting, or environmental changes, can be conserved through tissue culture techniques. By culturing small pieces of plant tissue, researchers can produce clones of rare species, thereby preserving genetic diversity and enabling the reintroduction of these plants into their natural habitats. Additionally, tissue culture techniques can be used to regenerate plants from seeds, embryos, or somatic cells, ensuring the long-term survival of endangered species and contributing to biodiversity conservation.

Tissue culture and micropropagation are indispensable tools in modern plant propagation, enabling the efficient multiplication of high-quality crops and the conservation of endangered plant species. These technologies are essential for preserving genetic resources, maintaining biodiversity, and ensuring sustainable agricultural and environmental practices. An effective example supporting the information on tissue culture and micropropagation is Orchids. Orchids are among the most sought-after ornamental plants, but they are notoriously difficult to propagate through conventional methods due to their complex growth requirements and slow reproduction rate (Mehub *et al.*, 2022) ^[47]. Through tissue culture and micropropagation, thousands of genetically uniform orchid plants can be produced from a single tissue sample.

This method allows for the mass production of healthy, disease-free orchids, ensuring their availability for commercial sale and conservation. Additionally, tissue culture techniques have been successfully employed in conserving endangered orchid species, such as the Lady's Slipper Orchid (*Cypripedium*), which faces threats from habitat loss (Tiware *et al.*, 2022) ^[69]. By propagating these rare species through tissue culture, scientists can maintain their genetic diversity and reintroduce them into protected environments, supporting biodiversity conservation. The success of tissue culture and micropropagation in orchids illustrates the broader potential of these techniques to preserve endangered

species, enhance agricultural productivity, and ensure the sustainability of plant resources for future generations.

Biopesticides and Biofertilizers

Biopesticides and biofertilizers represent an innovative approach to eco-friendly agricultural practices that promote sustainability and reduce the environmental impact of conventional chemical inputs. The development and usage of these biological alternatives are gaining momentum as part of a broader effort to achieve sustainable agriculture (Abbey *et al.*, 2019) ^[2]. Biopesticides, derived from natural organisms such as bacteria, fungi, and plants, offer effective control of pests and diseases while minimizing harm to non-target organisms, beneficial insects, and the environment. Biofertilizers, on the other hand, are living microorganisms that enhance soil fertility by promoting nutrient availability, improving soil structure, and increasing plant growth.

The development of biopesticides has been driven by the need to address the growing concerns about the adverse effects of synthetic chemical pesticides on human health, biodiversity, and ecosystems. Biopesticides are increasingly recognized for their ability to target specific pests or pathogens without causing the widespread ecological damage associated with traditional chemical pesticides. For example, *Bacillus thuringiensis* (Bt), a soil bacterium, is widely used as a biopesticide to control insect pests, particularly in crops like cotton and maize (Kumar *et al.*, 2021) ^[37]. Bt produces proteins that are toxic to certain insect larvae, offering a highly specific and environmentally friendly pest control solution. Other biopesticides, such as neem oil and pyrethrins, derived from plants, also provide effective pest management without leaving harmful residues in the environment. Biofertilizers have similarly emerged as a promising alternative to chemical fertilizers, which are known to degrade soil health over time and contribute to environmental pollution. Biofertilizers consist of beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi, which improve nutrient uptake and promote plant growth. For instance, *Rhizobium* species, which form symbiotic relationships with leguminous plants, fix atmospheric nitrogen and make it available to plants, reducing the need for synthetic nitrogen fertilizers (Abawari *et al.*, 2020) ^[1]. Similarly, arbuscular mycorrhizal fungi (AMF) help plants absorb phosphorus and other essential nutrients, enhancing plant growth and soil fertility.

The integration of biopesticides and biofertilizers into farming systems offers a sustainable and eco-friendly alternative to conventional chemical inputs. These biological agents can be used in conjunction with traditional farming practices to reduce dependence on synthetic chemicals, lower production costs, and enhance long-term soil health. Moreover, they contribute to the reduction of pesticide and fertilizer residues in food, ensuring safer and healthier produce for consumers (Tripathi *et al.*, 2020) ^[73]. As demand for organic and sustainable agricultural practices continues to rise, the development and widespread adoption of biopesticides and biofertilizers will play a key role in shaping the future of agriculture.

The development and usage of biopesticides and biofertilizers represent a significant step toward eco-friendly agricultural inputs that support sustainable crop production. By harnessing the power of natural organisms, these biological alternatives offer a promising solution to combat pests, enhance soil fertility, and improve plant health, while minimizing the environmental impact of conventional chemical inputs. The continued research, development, and commercialization of biopesticides and

biofertilizers will be crucial in advancing sustainable agricultural practices and ensuring the long-term health of the planet's ecosystems (Fenibo *et al.*, 2022) ^[21].

Synthetic Biology and CRISPR-Cas Technology

Synthetic biology and CRISPR-Cas technology have ushered in a new era of precision plant breeding, enabling the development of crops with improved yield and enhanced stress tolerance. These technologies allow for the targeted editing of plant genomes, offering a powerful tool to address global challenges such as climate change, water scarcity, and food insecurity. By using CRISPR-Cas9, a revolutionary genome-editing tool, scientists can precisely modify specific genes responsible for traits like drought resistance, pest resistance, and nutrient content. This level of precision reduces the need for traditional, labor-intensive breeding methods and accelerates the development of crops with desirable traits (Rai *et al.*, 2023) ^[56]. A prime example of CRISPR-Cas technology's potential is the development of drought-resistant rice. Researchers have successfully edited the *OsCPL1* gene, which plays a crucial role in water regulation, to enhance the rice plant's tolerance to drought conditions. The modified rice plants exhibited improved water retention capabilities without sacrificing yield, demonstrating how CRISPR can be used to make plants more resilient in the face of environmental stresses. This example highlights the ability of synthetic biology and CRISPR-Cas technology to create crops that not only withstand challenging growing conditions but also contribute to increased agricultural productivity. The precision offered by these technologies is paving the way for crops that are more resistant to environmental stresses, thereby improving food security and promoting sustainable agriculture. By enabling targeted genetic modifications, synthetic biology and CRISPR-Cas9 have the potential to revolutionize crop improvement, offering a solution to many of the challenges faced by modern agriculture (Sarnaik *et al.*, 2020) ^[65].

Microbial Biotechnology

Microbial biotechnology offers a multifaceted approach to improving soil fertility and crop health. By harnessing the natural capabilities of microorganisms, this field provides eco-friendly solutions to enhance agricultural productivity, reduce dependency on chemical inputs, and promote soil and plant health. The integration of microbial inoculants and biofertilizers into agricultural practices is a promising strategy for the sustainable development of agriculture. As an example, the use of *Trichoderma* species, a beneficial soil fungus, is widespread due to its ability to suppress soil-borne diseases, improve nutrient uptake, and boost plant growth (Sarnaik *et al.*, 2020) ^[65]. Additionally, the application of *Rhizobium* inoculants in legume crops has been shown to significantly increase nitrogen fixation, which enhances soil fertility and supports crop productivity. This highlights the critical role of microbial biotechnology in promoting sustainable agricultural practices that contribute to long-term environmental health and food security. By advancing the use of microbial inoculants and biofertilizers, this approach addresses the growing challenges of maintaining soil health, reducing chemical dependency, and ensuring robust crop production in the face of global agricultural demands.

3. Recent Advancements in Biotechnology in Agriculture

Precision agriculture (PA) represents a revolutionary shift in farming practices, enabling the optimization of agricultural operations through the integration of advanced technologies.

One of the key advancements in precision agriculture is the seamless integration of biotechnology with data analytics and the Internet of Things (IoT). This convergence facilitates more efficient, sustainable, and data-driven agricultural practices, resulting in enhanced crop yields, improved resource management, and reduced environmental impact (Rastegari *et al.*, 2020) ^[57].

Biotechnology plays a critical role in precision agriculture by providing innovative solutions for crop improvement, pest control, and soil health. Genetic engineering, for instance, allows for the development of crops with enhanced traits, such as resistance to pests, diseases, and environmental stresses, while also improving nutrient uptake and overall yield potential (Bailey-Serres *et al.*, 2019) ^[10]. Genetically modified (GM) crops, such as Bt cotton and drought-resistant maize, have already demonstrated their potential in improving crop performance under challenging conditions. Additionally, biotechnological applications, such as the use of biofertilizers and biopesticides, are key in promoting sustainable farming practices by reducing dependency on synthetic chemical inputs and preserving biodiversity.

Data analytics and IoT, on the other hand, provide farmers with real-time insights into various aspects of farm management. IoT-enabled devices, such as sensors, drones, and automated machinery, gather data on soil moisture, temperature, weather conditions, crop health, and nutrient levels. This data is then processed and analyzed using advanced algorithms, machine learning models, and predictive analytics to guide decision-making processes (Patil *et al.*, 2023) ^[52]. By integrating biotechnology with these technologies, farmers can optimize crop selection, monitor plant growth more accurately, apply fertilizers and pesticides precisely, and forecast harvest timings with higher accuracy. For example, IoT devices can monitor soil health, allowing farmers to track soil pH, moisture levels, and nutrient availability in real-time. When combined with biotechnological innovations, such as genetically engineered crops that are better suited to local soil conditions or resistant to specific pests, farmers can apply the right interventions at the right time. The data analytics platform then processes this information to generate actionable insights, enabling precise application of water, fertilizers, and pesticides, which reduces waste and increases efficiency. One key example is the integration of GM crops, such as drought-tolerant varieties of maize, with IoT-based systems in regions facing water scarcity (Amarasinghe *et al.*, n.d.) ^[5]. Sensors monitor soil moisture and crop health, and data analytics models predict the optimal watering schedule. The result is a more water-efficient farming system that improves crop yields while minimizing water usage, ensuring sustainability in water-scarce regions.

The integration of biotechnology with data analytics and IoT is transforming the landscape of precision agriculture. By combining the genetic improvements offered by biotechnology with the real-time data collection and analysis enabled by IoT, farmers can make informed decisions that optimize inputs, increase productivity, and enhance sustainability. As this integration continues to evolve, precision agriculture has the potential to play a pivotal role in addressing global food security challenges while minimizing the environmental footprint of farming.

Climate-Resilient Crops

Climate-resilient crops, bred to withstand heat, salinity, and flooding stresses, are critical in combating the agricultural challenges posed by climate change (Hafeez *et al.*, 2023) ^[27].

Advanced genetic tools, including marker-assisted selection (MAS), genome editing, and transgenic approaches, have enabled precise modifications to enhance stress tolerance in plants. For heat tolerance, genes like HSP and OsSPL14 have been targeted, leading to the development of crops like heat-resistant wheat varieties such as HD 2967 (Luo *et al.*, 2023) ^[42]. Salinity tolerance has been achieved by leveraging genes like NHX1, as seen in salt-tolerant tomatoes, and integrating traits from varieties like Pokkali into high-yielding rice strains such as IR64-Saltol. Flood tolerance has been enhanced by incorporating genes like SUB1A into rice, resulting in resilient varieties such as Swarna-Sub1 (Marwein *et al.*, 2019) ^[46]. Furthermore, genome-editing tools like CRISPR-Cas9 have facilitated precise genetic modifications, such as editing the OsRAV2 gene in rice for improved drought and heat tolerance. These innovations exemplify the transformative role of genetic tools in developing crops that ensure food security, sustainability, and resilience in the face of escalating climate challenges (Kissoudis *et al.*, 2016) ^[34].

Nanobiotechnology

Nanobiotechnology is emerging as a transformative tool in agriculture, offering innovative solutions for pest management, nutrient delivery, and disease diagnostics. By harnessing nanomaterials' unique properties, this interdisciplinary approach enhances agricultural productivity while promoting sustainability (Usman *et al.*, 2020) ^[76]. In pest management, nanoparticles have shown potential as efficient carriers for delivering biopesticides and chemical pesticides. For instance, silica nanoparticles have been used to deliver essential oils, increasing their stability and effectiveness against pests such as *Helicoverpa armigera*. Similarly, silver nanoparticles exhibit antimicrobial properties, providing a biocontrol mechanism against fungal pathogens like *Alternaria solani*. These nanopesticides offer targeted delivery, reducing environmental contamination and minimizing non-target effects. Nanotechnology also plays a significant role in nutrient delivery systems (Mandal, 2019) ^[44]. Nano-fertilizers, designed to release nutrients in a controlled manner, improve nutrient use efficiency and reduce wastage. For example, hydroxyapatite nanoparticles doped with nitrogen, phosphorus, and potassium have been developed to enhance the uptake of essential nutrients in maize. Such advancements ensure that crops receive a steady supply of nutrients, leading to higher yields while reducing the overuse of conventional fertilizers. In disease diagnostics, nanosensors provide rapid and highly sensitive detection of plant pathogens. Gold nanoparticles conjugated with specific antibodies have been used to detect viruses like *Tomato spotted wilt virus* at early stages, allowing for timely intervention. Additionally, carbon-based nanomaterials, such as graphene oxide, are being explored for detecting bacterial pathogens like *Xanthomonas campestris* in citrus crops (Vicente *et al.*, 2001) ^[78]. These applications exemplify how nanobiotechnology is revolutionizing agriculture. By improving pest control, nutrient efficiency, and disease management, this technology contributes to sustainable farming practices and enhances food security. For instance, the use of nanosensors in detecting citrus greening disease has significantly aided citrus growers in managing the disease and preventing its spread, showcasing the potential of nanobiotechnology in transforming agricultural systems.

Synthetic Seeds and Artificial Intelligence in Biotechnology

The integration of synthetic seeds and artificial intelligence (AI) within biotechnology is revolutionizing agricultural practices,

enabling precise and efficient solutions to enhance productivity and sustainability (Zhang *et al.*, 2024) ^[82]. Synthetic seeds, created by encapsulating somatic embryos or shoot buds in a protective gel-like coating, serve as an alternative to traditional seeds, offering advantages such as uniformity, disease resistance, and long-term storability. When combined with AI-driven technologies, these innovations pave the way for improved agricultural solutions. AI enhances the application of synthetic seeds by optimizing their production processes and predicting their performance under various environmental conditions. Machine learning models analyze vast datasets, such as genetic information, environmental factors, and growth patterns, to predict the most suitable conditions for synthetic seed germination and development (Niazian and Niedbała, 2020) ^[50]. For instance, AI-based algorithms can identify ideal nutrient formulations or encapsulation materials for synthetic seeds, ensuring higher germination rates and plant vigor.

In addition to synthetic seed development, AI contributes to precision agriculture by enabling real-time monitoring and decision-making. AI-powered platforms analyze data from sensors, drones, and satellite imagery to provide insights into soil health, crop status, and pest outbreaks (Niazian and Niedbała, 2020) ^[50]. This information supports the targeted use of synthetic seeds in degraded soils or areas prone to climatic stress, enhancing their effectiveness in promoting agricultural sustainability. A notable example of this synergy is the use of synthetic seeds for *Santalum album* (sandalwood) propagation. Sandalwood, a high-value tree species, faces challenges such as overharvesting and limited seed availability. Synthetic seeds, combined with AI tools for environmental prediction, have been used to ensure successful germination and growth under controlled conditions, aiding in the conservation and commercialization of this species (Bharathi *et al.*, 2023) ^[13].

This integration of synthetic seeds and AI exemplifies the future of biotechnology, where advanced computational tools and innovative biotechnological techniques converge to address global agricultural challenges. By leveraging AI to optimize synthetic seed use and enhance decision-making in agriculture, these advancements contribute to food security, resource efficiency, and environmental sustainability.

RNA Interference (RNAi) Technology

RNA interference (RNAi) is a biological mechanism through which gene expression is silenced at the post-transcriptional level. This process is mediated by small RNA molecules, such as small interfering RNA (siRNA) or microRNA (miRNA), which bind to complementary messenger RNA (mRNA) sequences, leading to their degradation or translational repression (Trčák, 2019) ^[71]. RNAi technology has become a cornerstone in pest and disease management, providing precise, eco-friendly, and sustainable solutions to agricultural challenges. In pest management, RNAi has been employed to target pest-specific genes essential for survival, reproduction, or physiological processes, resulting in pest mortality or reduced infestations. For instance, RNAi-based biopesticides have been developed to control the corn rootworm (*Diabrotica virgifera*), a significant pest in maize cultivation (Azad *et al.*, 2014) ^[9]. These biopesticides silence critical digestive or developmental genes, leading to pest-specific lethality without harming beneficial insects or the environment.

RNAi also offers promising solutions for combating plant diseases by silencing genes involved in pathogen virulence or host susceptibility. One example is the use of RNAi to develop crops resistant to viral diseases. In papaya, RNAi has been

utilized to confer resistance to the devastating Papaya Ringspot Virus (PRSV) by targeting viral replication genes, thereby protecting crops and improving yields. Similarly, RNAi has been applied to manage fungal pathogens by silencing genes critical for fungal growth or host infection. Moreover, RNAi technology is being integrated into strategies to manage resistance in pests and pathogens (Trčák, 2019) ^[71]. By designing double-stranded RNA (dsRNA) molecules targeting multiple genes or pathways, RNAi can help delay or overcome the evolution of resistance, ensuring the long-term effectiveness of pest and disease management strategies. In conclusion, RNAi technology offers a highly specific and environmentally sustainable approach to pest and disease management in agriculture. Its precision in targeting pests and pathogens, combined with its minimal impact on non-target organisms, underscores its potential to revolutionize agricultural practices (Azad *et al.*, 2014) ^[9]. With continued advancements and integration into crop protection systems, RNAi technology is poised to play a pivotal role in ensuring food security and sustainable farming.

Benefits of Biotechnology in Agriculture

Biotechnology has transformed agriculture by introducing innovative solutions to address food security, environmental sustainability, and economic challenges. Its applications have led to significant advancements in crop production, quality enhancement, and resource efficiency, making it a cornerstone of modern agricultural practices (Herdt, 2006) ^[30]. One of the most prominent benefits of biotechnology is the increased crop yield, which directly contributes to food security. Through genetic modification and precision breeding, crops have been engineered to exhibit traits like pest resistance, disease tolerance, and improved stress adaptation. For example, genetically modified (GM) Bt cotton has been instrumental in reducing crop losses due to bollworm infestations, enabling higher productivity and ensuring a stable supply of raw materials for the textile industry. Similarly, drought-tolerant maize varieties have been developed to thrive in arid conditions, addressing food shortages in water-scarce regions (Herdt, 2006) ^[30]. Biotechnology also plays a crucial role in reducing the environmental footprint of agriculture. Genetically modified crops with built-in pest resistance reduce the need for chemical pesticides, lowering environmental contamination and preserving biodiversity. Herbicide-tolerant crops like GM soybeans allow for more efficient weed management, which minimizes soil disturbance through reduced tillage practices. These advancements contribute to sustainable farming while mitigating the adverse effects of agriculture on ecosystems. Improved nutritional quality is another significant advantage of biotechnology. Crops such as Golden Rice, fortified with beta-carotene, address vitamin A deficiency in vulnerable populations, particularly in developing countries. Similarly, biofortified crops like iron-enriched beans and zinc-enhanced wheat help combat malnutrition by providing essential nutrients that are otherwise lacking in traditional diets.

Economic benefits for farmers and stakeholders are also substantial. Biotech crops reduce input costs by minimizing the need for pesticides, fertilizers, and water, leading to higher profitability for farmers. For instance, studies have shown that farmers cultivating GM crops like Bt cotton experience increased incomes due to reduced pest management expenses and enhanced yields (Herdt, 2006) ^[30]. Furthermore, biotechnology fosters economic growth in the agricultural sector by creating opportunities for biotech companies, researchers,

and allied industries. Biotechnology offers transformative benefits to agriculture by improving crop yields, enhancing food security, reducing environmental impact, and promoting economic growth. Its ability to create nutritionally superior crops and support sustainable farming practices highlights its importance in addressing global agricultural challenges. Examples such as Bt cotton, drought-tolerant maize, and biofortified Golden Rice exemplify the vast potential of biotechnology in shaping a resilient and sustainable future for agriculture.

Challenges and Ethical Concerns in Biotechnology

While biotechnology offers transformative solutions for agriculture and food security, it also raises significant challenges and ethical concerns that must be addressed to ensure its sustainable and equitable application. These challenges encompass public perception, biosafety, intellectual property rights, and economic accessibility, each of which has profound implications for the adoption and regulation of biotechnological innovations.

Public Perception and Acceptance

One of the most persistent challenges in biotechnology is public skepticism and resistance toward genetically modified organisms (GMOs). Concerns over the safety of GMOs for human consumption, their impact on biodiversity, and ethical questions surrounding genetic manipulation have fueled debates worldwide. The lack of transparent communication about the benefits and risks of GMOs has further exacerbated public mistrust. Regulatory frameworks, such as the Cartagena Protocol on Biosafety, have been established to address these concerns, mandating risk assessments and labeling to ensure the safe use of GM products. However, public acceptance remains varied across regions, influenced by cultural, social, and political factors. For instance, the controversy surrounding Golden Rice, a genetically modified crop enriched with Vitamin A, highlights public and regulatory hesitations despite its potential to combat malnutrition in developing countries.

Biosafety and Biosecurity

The introduction of biotech products into the environment and food systems necessitates thorough risk assessments to prevent unintended consequences. Potential risks include gene flow from GM crops to wild relatives, the emergence of resistant pests or weeds, and unintended effects on non-target organisms (Zaki, 2010)^[81]. For example, Bt cotton, engineered to produce a toxin to combat bollworms, has raised concerns about the potential development of resistance in target pests and its impact on beneficial insects. Biosafety regulations aim to minimize these risks, but enforcement and monitoring remain challenging in regions with limited resources. Additionally, biosecurity concerns arise from the potential misuse of biotechnological tools for harmful purposes, necessitating international cooperation to establish robust safeguards (Zaki, 2010)^[81].

Intellectual Property Rights (IPR)

The protection of biotechnological innovations through patents has spurred debates over accessibility and equity. While IPR incentivizes innovation, it can also create monopolies that limit access to advanced technologies for small-scale farmers and developing countries (Bragdon, 2016)^[15]. For instance, the controversy over Monsanto's patented Roundup Ready soybeans

illustrates the tension between innovation and farmers' rights. Legal disputes regarding seed-saving practices and the dependency created by patented seeds have drawn criticism, highlighting the need for balanced IPR policies. Reforming these frameworks to promote equitable access without stifling innovation is a key challenge.

Cost and Accessibility

The economic barriers associated with biotechnological tools, including high research and development costs, regulatory compliance expenses, and the price of biotech products, pose significant challenges to widespread adoption. Small-scale farmers, particularly in developing countries, often lack the financial resources and technical knowledge to utilize these innovations effectively. For example, precision agriculture technologies, such as drones for crop monitoring and variable rate applicators for fertilizers, are often cost-prohibitive for resource-poor farmers. Efforts to address these disparities include public-private partnerships, subsidies, and the development of low-cost alternatives tailored to the needs of smallholder farmers.

Future Directions and Prospects

The future of biotechnology in agriculture is shaped by emerging technologies such as CRISPR, synthetic biology, and artificial intelligence (AI), which hold immense potential to revolutionize crop production and address global challenges like climate change and food security. CRISPR enables precise gene-editing for developing crops with enhanced resistance to pests, diseases, and environmental stresses, while synthetic biology allows for the creation of crops with novel traits like improved nitrogen fixation and enhanced nutritional content. AI, on the other hand, enhances precision agriculture by enabling data-driven decision-making for optimized farming practices, pest control, and crop monitoring. Biotechnology also plays a critical role in sustainability and climate-smart agriculture by developing drought-tolerant and heat-resistant crops, improving nutrient use efficiency, and reducing chemical inputs. Collaborative efforts between governments, academia, and industry are essential for advancing these innovations, ensuring their safe deployment, and making them accessible to farmers worldwide.

Conclusion

Biotechnology is revolutionizing agriculture by enhancing crop yield, nutritional quality, and stress tolerance, addressing challenges like food security and climate change. Techniques such as CRISPR, synthetic biology, and microbial biotechnology offer sustainable solutions for pest management and nutrient delivery. However, balancing innovation with sustainability is crucial, ensuring that these technologies are used responsibly with ethical considerations and rigorous risk assessments. Collaboration among governments, academia, industry, and farmers is key to ensuring biotechnology benefits both the environment and society, shaping a resilient and food-secure future for all.

Reference

1. Abawari RA, Tuji FA, Yadete DM. Phosphate solubilizing bio-fertilizers and their role in bio-available P nutrient: an overview. *Int. J Appl Agric Sci.* 2020;6(6):162.
2. Abbey L, Abbey J, Leke-Aladekoba A, Iheshiulo EMA, Ijenyo M. Biopesticides and biofertilizers: types, production, benefits, and utilization. In: *Byproducts from*

- agriculture and fisheries: adding value for food, feed, pharma, and fuels. 2019. p. 479-500.
3. Abdi G, Patil N, Mishra P, Tariq M, Dhariwal R, Parveen S, *et al.* Genomic Precision: Unveiling the Transformative Role of Genome Editing in Advancing Genomics Research and Applications. In: *Advances in Genomics: Methods and Applications*. Singapore: Springer Nature Singapore; 2024. p. 265-306.
 4. Adams MR. The birth of modern industrial microbiology: the acetone-butanol fermentation. *Int. J Hist Eng Technol.* 2017;87(1):81-95.
 5. Amarasinghe AAY, Amarasinghe STC, Polwaththa KPGDM. Biotechnological tools in precision and smart agriculture: Innovations, sustainability, and economic impacts.
 6. Ammerman AJ, Cavalli-Sforza LL. The Neolithic transition and the genetics of populations in Europe. Princeton University Press, 2014, 836.
 7. Anyshchenko A. Aligning Policy Design With Science to Achieve Food Security: The Contribution of Genome Editing to Sustainable Agriculture. *Front Sustain Food Syst.* 2022;6:897643.
 8. Asghar W, Akça MO, Akça H, Tarf OJ, Kataoka R, Turgay OC. Alternative strategies to synthetic chemical fertilizers: revitalization of soil quality for sustainable agriculture using organic-based approaches. In: *New and future developments in microbial biotechnology and bioengineering*. Elsevier; 2022. p. 1-30.
 9. Azad MAK, Amin L, Sidik NM. Gene technology for papaya ringspot virus disease management. *Sci World J.* 2014;2014(1):768038.
 10. Bailey-Serres J, Parker JE, Ainsworth EA, Oldroyd GE, Schroeder JI. Genetic strategies for improving crop yields. *Nature.* 2019;575(7781):109-118.
 11. Balasubramanian P, Karthickumar P. Biofertilizers and biopesticides: A holistic approach for sustainable agriculture. In: *Sustainable utilization of natural resources*. CRC Press; 2017. p. 255-284.
 12. Betz UA, Arora L, Assal RA, Azevedo H, Baldwin J, Becker MS, *et al.* Game changers in science and technology-now and beyond. *Technol Forecast Soc Change.* 2023;193:122588.
 13. Bharathi JK, Anandan R, Benjamin LK, Muneer S, Prakash MAS. Recent trends and advances of RNA interference (RNAi) to improve agricultural crops and enhance their resilience to biotic and abiotic stresses. *Plant Physiol Biochem.* 2023;194:600-618.
 14. Bilal MF, Saleem MF, Wahid MA, Shakeel A, Maqbool M. Adoption of Bt cotton: Threats and challenges. *Chilean J Agric Res.* 2012;72(3):419-425.
 15. Bragdon SH. Reinvigorating the public sector: The case of food security, small-scale farmers, trade and intellectual property rules.
 16. Carvalho FP. Agriculture, pesticides, food security and food safety. *Environ Sci Policy.* 2006;9(7-8):685-692.
 17. Crowe N. The Historiography of Biotechnology. In: *Handbook of the Historiography of Biology*. 2021. p. 217-241.
 18. El-Mansi M. Fermentation microbiology and biotechnology: An historical perspective. In: *Fermentation Microbiology and Biotechnology*, Fourth Edition. CRC Press; 2018. p. 3-8.
 19. Ervin DE, Glenna LL, Jussaume Jr RA. Are biotechnology and sustainable agriculture compatible?. *Renew Agric Food Syst.* 2010;25(2):143-157.
 20. Fatima G, Magomedova A, Parvez S. *Biotechnology and Sustainable Development*. Shineeks Publishers; 2024.
 21. Fenibo EO, Ijoma GN, Matambo T. Biopesticides in sustainable agriculture: Current status and future prospects. In: *New and future development in biopesticide research: biotechnological exploration*. 2022. p. 1-53.
 22. Fu YB. Understanding crop genetic diversity under modern plant breeding. *Theor Appl Genet.* 2015;128:2131-142.
 23. Ganguly K, Gulati A, von Braun J. Innovations spearheading the next transformations in India's agriculture.
 24. Gomollón-Bel F. IUPAC Top Ten Emerging Technologies in Chemistry 2022: Discover the innovations that will transform energy, health, and materials science, to tackle the most urgent societal challenges and catalyse sustainable development. *Chem Int.* 2022;44(4):4-13.
 25. Goodman RE. Biosafety: Evaluation and regulation of genetically modified (GM) crops in the United States.
 26. Goyal MR. *Scientific and Technical Terms in Bioengineering and Biological Engineering*. CRC Press; 2018.
 27. Hafeez U, Ali M, Hassan SM, Akram MA, Zafar A. Advances in breeding and engineering climate-resilient crops: A comprehensive review. *Int. J Res Adv Agric Sci.* 2023;2(2):85-99.
 28. Hafeez U, Ali M, Hassan SM, Akram MA, Zafar A. Advances in breeding and engineering climate-resilient crops: A comprehensive review. *Int. J Res Adv Agric Sci.* 2023;2(2):85-99.
 29. Hassan EA, Abdolkader TM. A review of ion-sensitive field effect transistor (ISFET) based biosensors. *Int. J Mater Technol Innov.* 2023.
 30. Herdt RW. Biotechnology in agriculture. *Annu Rev Environ Resour.* 2006;31(1):265-295.
 31. Hulse JH. Biotechnologies: past history, present state and future prospects. *Trends Food Sci Technol.* 2004;15(1):3-18.
 32. Jiang GL. Molecular markers and marker-assisted breeding in plants. In: *Plant breeding from laboratories to fields*. 2013. p. 45-83.
 33. Joshi BK, Shrestha HK, Ayer DK. Crop Breeding and Biotechnological Advances towards Nutrition and Environment Security. In: *Emerging Solutions in Sustainable Food and Nutrition Security*. Cham: Springer International Publishing; 2023. p. 255-285.
 34. Kissoudis C, Van De Wiel C, Visser RG, Van Der Linden G. Future-proof crops: challenges and strategies for climate resilience improvement. *Curr Opin Plant Biol.* 2016;30:47-56.
 35. Kour D, Rana KL, Yadav AN, Yadav N, Kumar M, Kumar V, *et al.* Microbial biofertilizers: Bioresources and eco-friendly technologies for agricultural and environmental sustainability. *Biocatal Agric Biotechnol.* 2020;23:101487.
 36. Kowalski SP. Golden rice, open innovation, and sustainable global food security. *Ind Biotechnol.* 2015;11(2):84-90.
 37. Kumar J, Ramlal A, Mallick D, Mishra V. An overview of some biopesticides and their importance in plant protection for commercial acceptance. *Plants.* 2021;10(6):1185.
 38. Kumar KP, Walia P. Speed breeding in cereal crops: Accelerating genetic improvement for rapid agricultural advancement. *J Exp Agric Int.* 2024;46(6):465-477.
 39. Lee H, Krinsky S. The arrested development of Golden Rice: the scientific and social challenges of a transgenic biofortified crop. *Int J Soc Sci Stud.* 2016;4:51-59.

40. Li D, Tang Y, Lin J, Cai W. Methods for genetic transformation of filamentous fungi. *Microb Cell Fact*. 2017;16:1-13.
41. Libengood J. At the intersection of human agency and technology: genetically modified organisms. University of South Florida; 2015.
42. Luo L, Xie Y, Yu S, Yang J, Chen S, Yuan X, *et al*. The DnaJ domain-containing heat-shock protein NAL11 determines plant architecture by mediating gibberellin homeostasis in rice (*Oryza sativa*). *New Phytol*. 2023;237(6):2163-2179.
43. Malabadi RB, Nethravathi TL, Kolkar KP, Chalannavar RK, Mudigoudra BS, Lavanya L, *et al*. Cannabis sativa: applications of artificial intelligence and plant tissue culture for micropropagation. *Int. J Res Innov Appl Sci*. 2023;8(6):117-142.
44. Mandal BK. Silver nanoparticles: potential as insecticidal and microbial biopesticides. In: *Nano-biopesticides today and future perspectives*. Academic Press; 2019. p. 281-302.
45. Mapari AR, Mehendi S. Enhancing crop resilience: advances and challenges in marker-assisted selection for disease resistance. *J Adv Biol Biotechnol*. 2024;27(7):569-580.
46. Marwein R, Debbarma J, Sarki YN, Baruah I, Saikia B, Boruah HD, *et al*. Genetic engineering/genome editing approaches to modulate signaling processes in abiotic stress tolerance. In: *Plant signaling molecules*. Woodhead Publishing; 2019. p. 63-82.
47. Mehbub H, Akter A, Akter MA, Mandal MS, Hoque MA, Tuleja M, *et al*. Tissue culture in ornamentals: cultivation factors, propagation techniques, and its application. *Plants*. 2022;11(23):3208.
48. Meyer S. The Neolithic revolution. The Rosen Publishing Group, Inc.; 2016.
49. Mosier NS, Ladisch MR. Modern biotechnology: connecting innovations in microbiology and biochemistry to engineering fundamentals. John Wiley & Sons; 2011.
50. Niazian M, Niedbala G. Machine learning for plant breeding and biotechnology. *Agriculture*. 2020;10(10):436.
51. Pardo-López L, Soberón M, Bravo A. Bacillus thuringiensis insecticidal three-domain Cry toxins: mode of action, insect resistance and consequences for crop protection. *FEMS Microbiol Rev*. 2013;37(1):3-22.
52. Patil BD, Gupta S, Sheikh AI, Lalitha SS, Raj KD. IoT and Big Data Integration for Real-Time Agricultural Monitoring. *J Adv Zool*. 2023;44:3079-89.
53. Pithiya MB, Sharma SK, Sharma M, Sharma M, Neeraj Kotwal. Advancements and Challenges in Plant Tissue Culture: A Comprehensive Overview. *J Plant Biota*. 2022; 29: 1-24.
54. Priyanka V, Kumar R, Dhaliwal I, Kaushik P. Germplasm conservation: instrumental in agricultural biodiversity-a review. *Sustainability*. 2021;13(12):6743.
55. Pulikkottil JA. Grey matter dialogues: A journey on economics and history of science and technology. Partridge Publishing; 2017.
56. Rai GK, Khanday DM, Kumar P, Magotra I, Choudhary SM, Kosser R, *et al*. Enhancing crop resilience to drought stress through CRISPR-Cas9 genome editing. *Plants*. 2023;12(12):2306.
57. Rastegari AA, Yadav AN, Yadav N, editors. New and future developments in microbial biotechnology and bioengineering: trends of microbial biotechnology for sustainable agriculture and biomedicine systems: diversity and functional perspectives. Elsevier; 2020.
58. Rauf S, Al-Khayri JM, Zaharieva M, Monneveux P, Khalil F. Breeding strategies to enhance drought tolerance in crops. In: *Advances in plant breeding strategies: agronomic, abiotic and biotic stress traits*. 2016. p. 397-445.
59. Ruane J, Sonnino A. Agricultural biotechnologies in developing countries and their possible contribution to food security. *J Biotechnol*. 2011;156(4):356-363.
60. Ruggiero A, Punzo P, Landi S, Costa A, Van Oosten MJ, Grillo S. Improving plant water use efficiency through molecular genetics. *Horticulturae*. 2017;3(2):31.
61. Ruse M. Genetic prehistory in selective breeding: a prelude to Mendel. 2002.
62. Sahu A, Mishra S, Shatrusal AK. Biofuels: A sustainable path to renewable energy. Sampath V, Rangarajan N, CH S, Deori M, Veeraragavan M, Ghodake BD, *et al*. 2022.
63. Kaushal K. Advancing crop improvement through CRISPR technology in precision agriculture trends—a review. *Int. J Environ Climate Change*. 2023;13(11):4683-4694.
64. Sarkar M, Gupta J. Biotechnological interventions to mitigate the influence of climate alterations on ecosystem viability and human well-being. In: *Unraveling new frontiers and advances in bioinformatics*. Singapore: Springer Nature Singapore; 2024. p. 387-407.
65. Sarnaik A, Liu A, Nielsen D, Varman AM. High-throughput screening for efficient microbial biotechnology. *Curr Opin Biotechnol*. 2020;64:141-150.
66. Singh A, Rajput V, Singh AK, Sengar RS, Singh RK, Minkina T. Transformation techniques and their role in crop improvements: a global scenario of GM crops. In: *Policy issues in genetically modified crops*. Academic Press; 2021. p. 515-42.
67. Singh BD, Singh AK. Marker-assisted plant breeding: principles and practices. 2015.
68. Taveira IC, Nogueira KMV, Oliveira DLGD, Silva RDN. Fermentation: humanity's oldest biotechnological tool. 2021.
69. Tiwari P, Sharma A, Bose SK, Gautam A. Biotechnological interventions in Orchids: recent updates, translational success, and commercial outcomes. 2022.
70. Toro MA. Future trends in animal breeding due to new genetic technologies. *Adv Anim Biosci*. 2011;1(3):546-557.
71. Trčak M. Use and application of RNA interference in plant protection: case study on Western Corn Rootworm. [Doctoral dissertation]. University of Zagreb, Faculty of Agriculture; 2019.
72. Tripathi MK, Tiwari S, Tripathi N, Tiwari G, Bhatt D, Vibhute M, *et al*. Plant tissue culture techniques for conservation of biodiversity of some plants appropriate propagation in degraded and temperate areas. *Current Topics in Agricultural Sciences*. BP International Publisher: Bhanjipur, India; 2021.
73. Tripathi S, Srivastava P, Devi RS, Bhadouria R. Influence of synthetic fertilizers and pesticides on soil health and soil microbiology. In: *Agrochemicals detection, treatment and remediation*. Butterworth-Heinemann; 2020. p. 25-54.
74. Tylecote A. Biotechnology as a new techno-economic paradigm that will help drive the world economy and mitigate climate change. *Res Policy*. 2019;48(4):858-868.
75. Udegbe FC, Ebulue OR, Ebulue CC, Ekesiobi CS. Synthetic biology and its potential in US medical therapeutics: A comprehensive review: exploring the cutting-edge intersections of biology and engineering in drug development and treatments. *Eng Sci Technol J*.

- 2024;5(4):1395-1414.
76. Usman M, Farooq M, Wakeel A, Nawaz A, Cheema SA, ur Rehman H, *et al.* Nanotechnology in agriculture: Current status, challenges and future opportunities. *Sci Total Environ.* 2020;721:137778.
 77. Venugopalan MV, Sankaranarayanan K, Blaise D, Nalayini P, Prahraj CS, Gangaiah B. Bt cotton (*Gossypium* sp.) in India and its agronomic requirements-a review. *Indian J Agron.* 2009;54(4):343-360.
 78. Vicente JG, Conway J, Roberts SJ, Taylor JD. Identification and origin of *Xanthomonas campestris* pv. *campestris* races and related pathovars. *Phytopathology.* 2001;91(5):492-499.
 79. Yi D. The recombinant university: genetic engineering and the emergence of biotechnology at Stanford, 1959-1980. Princeton University; 2008.
 80. Zafar MM, Razzaq A, Farooq MA, Rehman A, Firdous H, Shakeel A, *et al.* Insect resistance management in *Bacillus thuringiensis* cotton by MGPS (Multiple genes pyramiding and silencing). *J Cotton Res.* 2020;3:1-13.
 81. Zaki AN. Biosafety and biosecurity measures: management of biosafety level 3 facilities. *Int. J Antimicrob Agents.* 2010;36(S70-S74).
 82. Zhang D, Xu F, Wang F, Le L, Pu L. Synthetic biology and artificial intelligence in crop improvement. *Plant Commun.* 2024.
 83. Zaki AN. Biosafety and biosecurity measures: management of biosafety level 3 facilities. *Int. J Antimicrob Agents.* 2010, 36(S70-S74).
 84. Zhang D, Xu F, Wang F, Le L, Pu L. Synthetic biology and artificial intelligence in crop improvement. *Plant Commun.* 2024;5(1):1-14.