FUTURE DIRECTIONS IN AGRICULTURE BIOTECHNOLOGY: DEVELOPING RESILIENT AND SUSTAINABLE AGRICULTURE SYSTEMS

Abstract

As the global population continues to grow, ensuring security and sustainability of food becomes increasingly challenging. One of them is scientific disciplines with the greatest growth is biotechnology, which has greatly advancement a number of disciplines including agriculture, medical, pharmaceutical industry, and environmental science. Agricultural biotechnology has emerged as a vital tool to address the challenges faced by the global agriculture sector. However, their acceptance and utilization also provide major challenges, particularly for small-scale production. This book chapter provides an extensive overview of emerging trends, recent advancements, and potential applications of agriculture biotechnology that are expected to shape the future of food production. It explores novel technologies, such as genetic modification, gene editing, synthetic biology, nanotechnology, industrial biotechnology, precision agriculture, and their potential contributions to improving crop productivity, resource efficiency, disease resistant, nutritional quality and environmental sustainability. This chapter also highlights the necessity of responsible and inclusive innovation, considering social, ethical, and regulatory aspects for efficient implementation.

Keywords: Agricultural biotechnology, nutritional quality, novel technologies, crop productivity.

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I. INTRODUCTION

By 2050 growing populations, particularly in developing nation, would necessitate a 70% increase in crop yields. It will be necessary to raise food production by between 25% and 100% to fulfill this increasing demand for food (Hunter et al. 2017). Making the major improvement of agricultural productivity over the next few decades a top priority. Biotechnology has focused its efforts in this area on developing.New high – yielding varieties of the cereal, grains, wheat, rice, and maize were developed during the relatively recent Green Revolution of the 1960s as a result of international research investment in the field of agriculture. These varieties were widely cultivated and increased food security across the globe (Pingaliet al. 2012).Climate change also poses a significant threat to agriculture and food production. Rising temperatures, changes in precipitation patterns, and adverse conditions can damage livestock health, disrupt crop growth, and impact food production and supply system. Both reducing greenhouse gas emissions and adapting agriculture to climate change are major challenges. By developing crop varieties with improved drought tolerance, heat tolerance, flood resistance, and salinity tolerance, biotechnology can contribute to more resilient agricultural systems. These crops can better withstand extreme weather events and adapt to changing climatic conditions. Unsustainable practices of agriculture, deforestation and extensive use of land result in erosion of soil, decreased fertility, and decreasing crop productivity (Calabiet al. 2018).

Promote and support the utilization of sustainable agricultural practices as agroforestry, conservation agriculture, organic farming, and precision agriculture. Such practices can help to improve soil quality, decrease greenhouse gas emission, conserve water resources and protect biodiversity. The main aim of developing sustainable agricultural methods are reducing the burden on the environment and ecosystem, avoiding the use of chemical fertilizers, pestisides, and herbicides and protecting the atmosphere (Frisvold et al. 2007). Meeting the growing global demand for food while minimizing environmental impact requires sustainable intensification of agriculture. Balancing productivity with environmental sustainability and minimizing resource use, such as water, energy, and fertilizers, is a key challenge. Additionally, rapid use of those products may promote the accumulation of hazardous substances in the soils. In fact, it has been proven that potatoes can absorb some pesticides from the soil (Juraske et al. 2011).Despite the lack of knowledge on this issue, we are able to conclude that crop plants have the ability to absorb these substances from the soil, that poses an unidentified risk to both humans as well as the ecosystem (Juraske et al. 2011).However, traditional agriculture believes that these benefits are only for short term and even poses a serious long term threat to ecosystem(Bochtis et al. 2014).

Urbanization and land degradation are steadily reducing the quantity of land that can be used for food production, and this trend is projected to be much more pronounced in emerging nations than in developed nations (Sharma et al. 2002). This presents a pressing need for innovative solutions to ensure sustainable and efficient food production. Multiple solutions involving social, economic and technological changes will be needed to address the challenges in order to maintain food security (Tietjen et al. 2017). Biotechnology offers promising opportunities to address these challenges by enhancing crop production, improving pests and diseases resistance, and developing more nutritious and resilient crops. The scope of biotechnology is continually expanding as advancements are made in areas like genomics, gene editing, nanotechnology, and other interdisciplinary fields.Although a wide range of food products have been produced because to technology advances, society is demanding foods that are safer and of greater quality. The demonstrated added value of society have made customers more susceptible to use organic products (Gutiérrez-Cedillo et al. 2008).A broad spectrum of technologies are used by scientists in modern agricultural biotechnology to comprehend and alter the genetic structure of various species for use in the cultivation or processing of crops and other agricultural products. In order to solve these issues in all aspects of crop yield and manufacturing, modern terms of biotechnology is being applied. As novel tools emerge over time and are built on the use of enhanced technological breakthroughs and a greater grasp of various life science concepts, the complexity of biotechnology increases (Vermaet al. 2011).

The important role of biotechnology in modern society is evident in its contributions to healthcare, agriculture sustainability, and environmental conservation.It holds the potential to address global challenges, improve human health, enhance food security, and contribute to sustainable development. However, it is crucial to balance the benefits of biotechnology with responsible and ethical considerations to ensure its safe and responsible application.Biotechnology has made significant historical contributions to the advancement of both agriculture andthe food industries. Thedevelopment of feeding resources has made use of chemicals compounds and microorganism that providing the general people with a wider variety of food. Biotechnology has made advances in strategies to increase crop yields and supply food for the growing population. In order to enhance micronutrient density of food, biotechnology has developed methods like genetic manipulation (Cano Estradaet al. 2017).

By using the genes, we can providetolerance or resistance to biotic and abiotic stresses, reducing our dependence on agro-chemicals, especially pesticides, and increasing productivity and quality. As well, with the help of advancements in technology for producing biomass-derived energy, increased the rate of nitrogen fixation and nutrient absorption and use efficiency prevent the production of excessive amounts of nutrient in nutrient-deficient soils. These are several ways that biotechnology generally contributes to sustainable agriculture (Persley and Lantin 2000).

In this book chapter, we try to offer a critical yet helpful perspective on the potential and limitations of various biotechnological advancements and their usage to improve crop production.

II. GMOS APPLIED FOR CROP IMPROVEMENT

Genetically modified organisms (GMOs) have been applied widely for crop development purposes. GMOs are individual organisms whose genetic material has been modified through genetic engineering techniques in order to introduce or modify specific traits.GMOs have been developed to introduce traits that would improve crop yield via, enhanced resistance to diseases, pests, or environmental stresses. For example, genetically modified crop varieties with built-in resistance to certain insects or herbicides have helped reduce crop losses and improve overall productivity. Around 32 crops containing 525 unique transgenic traits have already been given authorization for international cultivation (ISAAA database 2019). The most events among these are related to maize, cotton, potatoes, soybeans, carnations and others (ISAAA database 2019). According to information, theapplicationof genetically engineered crops enhance crop yields, lowers CO2 emissions, decreases the use of pesticide and insecticide, and decreases the cost of agriculture.Weeds compete with field crops for vitamins, minerals and other environmental factors, which results in significant output losses(Kumar et al. 2020). Genetic engineering techniques have allowed developing many cultivars for crop that are resistant to specific herbicides. This trait enables farmers to effectively control weeds without harming the crop plants. Herbicide-tolerant GMOs have facilitated more efficient weed management practices and reduced the reliance on manual labor and intensive herbicide use.GMOs withresistance abilityto biotic and abiotic stresses may also mitigate the effects ofclimate change on crop production.

Genetically modified plants are those that are created when certain foreign genetic material or gene sequences are inserted into their genome, which are commonly referred to as transgenic, can be modified by applying transformation techniques to distinct species of animals, bacterium, viruses, fungus, or plants (for example, Agrobacterium-mediated transformation or direct gene transfer methods) (Grifths et al. 2005). GMOscan built-in pest or disease resistance can be highly effective initially, but prolonged and exclusive use of these traits can lead to the enhancement of resistance. Integrated pest management (IPM) strategies should also be implemented alongside GMOs, incorporating a combination of cultural, biological, and chemical control methods. Rotation of different pest management strategies and cultivation practices can help minimize resistance development. Diseases and insects seriously reduces the crop yield. There are more than 67,000 distinct species of insects that damage significant agricultural crops. By sucking sap or intake of plant materials like leaves, stems, and roots,and destroy crops. Furthermore, insects act as transmitters for several plant diseases that transmit from plant to insects during feeding (Rahman et al. 2021).

Genetic modification can confer resistance to pests and diseases in crops. This is often achieved by incorporating genes from other organisms that produce natural defense mechanisms. For example, scientists have developed genetically modified (GM) crops like Bt cotton, which produces a natural pesticide that protects the plants against certain insect pests. By incorporating traits like pest resistance, GMOs can reduce the need for chemical pesticides, leading to lower chemical inputs and decreased environmental impact (Grifths et al. 2005). A good example of biofortification is increasing the levels of essential vitamins and minerals,or other nutrients in agricultural crops to address nutritional shortages in particular populations. Vitamin levels have been boosted in GMOs, such as the golden rice that is genetically modified to generate more beta-carotene, a precursor to vitamin A. GMOs offer a precise and efficient means of introducing specific traits into crops. Traditional breeding methods often involve lengthy and unpredictable processes, while genetic modification allows for the direct transferof desired genes. Genetically modified organisms (GMOs) can be crossed with conventional breeding lines to introduce the desired trait into commercially viable varieties. This precision enables the improvement of various crop varieties with targeted genes, accelerating the breeding process and facilitating crop improvement efforts. Trait stacking refers to the process of introducing multiple genes or traits into a single organism to achieve multiple desired characteristics.

Although there are obstacles to the global use of genetically modified crops. These obstacles also consist of concerns regarding potential human toxicity and allergenicity, potential environmental risks such as the possibility of gene flow, adverse effects on organisms that are targeted, the evolution of resistance in weeds and insects etc. (Kumar et al. 2020).Different countries have varying regulatory approaches, and harmonizing regulations globally can be challenging.To overcome this challenge, rigorous and comprehensive environmental risk assessment protocols should be implemented, including long-term monitoring and adaptive management practices. As a result of ongoing research and development, GMOs with reduced environmental risks and enhanced ecological compatibility can possibly be developed.

In contrast to this background, the book chapter cover the present status of agriculturally produced transgenic crops containing multiple features such as public concerns about genetic manipulation tools for crops and potential biosafety issues related to the use of transgenic agricultural crops. Additionally offer future prospects about the potential of agricultural crops that have been altered utilizing genome editing technology (Kumar et al. 2020).Implementing comprehensive monitoring and evaluation systems to assess the long-term impacts of genetically modified crops is crucial. This includes monitoring ecological interactions, biodiversity, health effects, and socio-economic aspects. Regular review and adjustment of regulatory frameworks based on scientific findings can help ensure the continued safety and sustainability of genetic engineering in agriculture.

By adopting these strategies and promoting an inclusive, transparent, and scientifically informed approach, it is possible to overcome challenges associated with genetic engineering in agriculture and harness its potential for sustainable and improved crop varieties.

III. GENETIC ENGINEERING TO IMPROVE CROP VARIETIES

Genetic engineering techniques are constantly evolving, and new methods, such as gene editing technologies like ZFNs (Zinc Finger Nucleases), TALENs (Transcription Activator-Like Effector Nucleases) and CRISPR(Clustered Regularly Interspaced Short Palindromic Repeats)-Cas9, are being develop. These techniques offer more precise and efficient ways to modify organism’s genomes, gene editing, or genetic engineering are terms used to describe techniques used to introduce precise modifications into the genetic material of organisms (Baltes et al. 2017).

These involve techniques for introducing genetic material, the development of vector systems, and the use of modified proteins (Jansing et al. 2019). The ZFNs and TALENs are examples of the first current generation of techniques for editing genomes in crops. ZFNs have been applied effectively for genetic modifications in many plant species, although the method still has certain drawbacks (Chen et al. 2019). The primary limitation of ZFNs is the requirement for numerous VRRs to act on a single target. One of them emerging technique for plant and crop improvement is genome editing using technologies such as CRISPR-Cas9. CRISPR-Cas9 enables precise gene editing or modification that alter the genetic material of any organism, even plants (Anzalone et al. 2020).

Plant structures, biomass, quantity and size of fruit and/or grains are a few examples of variables affecting productivity (Chen et al. 2019). Techniques of genetic engineering in agriculture involve the modifications of an organism's genetic material to introducespecific traits. Genetic engineering has been used to develop crops that are resistant to certain diseases caused by viruses, bacteria, fungi, or other pathogens (Barrangouet al. 2007). Additionally, it can increase the amount of vitamins in crops or increase their nutritional value(Damattaet al. 2014)For example, the plants of *Camelina sativa*(False flax) and *Brassica napus*(Canola) produce seeds with higholeic acid content after genome editing (Jiang et al. 2017; Huang et al. 2020).

Genetic improvement in cropsplays an important role in enhancing crop yield and stress tolerance. This involves the selection and modification of crop varieties with desirable traits including high yield potential, drought tolerance, salt tolerance, and nutrient use efficiency (Ricrochet al. 2016). However, it is important to note that the use of gene editing technique like CRISPR-Cas9 in agriculture is a topic of ongoing debate and regulation (Baltes et al. 2017). The technology raises environmental and regulatory considerations that need to be carefully addressed to ensure responsible and safe implementation. Regulatory frameworks vary across countries and regions, and the technology's usage is subject to specific guidelines and regulations in different areas. For example, Citrus canker robust orange lines were developed by altering the promoter region and coding regions of a gene(Peng et al. 2017). Many research investigations show the effectiveness of CRISPR-Cas9 against various DNA viruses (Ali et al. 2015).

The application of CRISPR-Cas9 in plant and crop improvement has several potential benefits. By enhancing plant resistance to pests and diseases, it is possible to improve crop production(Brown et al. 2002). For example, to improve grain length and grain weight in two wheat varieties by knockout of three TaGASR7 homologues using genetic factors (Zhang et al. 2016).Genetic engineering involves complex biological processes and interactions. Due to the complexity ofunderstanding the function and interaction of genes within an organism's genome, thisis a challenging task.But compared to traditional gene modification methods, CRISPR-Cas9 offers several advantages. It allows for more precise and targeted modifications, reducing the potential for unintended changes. The process is also faster compared to traditional breeding, as it can take years or even decades to achieve similar results through conventional methods. Moreover, CRISPR-Cas9 enables the modification of crop varieties that may be challenging or impossible to achieve through traditional breeding methods.CRISPR and other biotechnological tools are being combined in novel ways to develop genome editing technologies (Anzalone et al. 2020). Investigating in research on safety, environmental impacts, and long term effects of genetically modified crops can help address uncertainties and mitigate risks.

Overall, genome editing techniques like CRISPR-Cas9 hold significant potential for plant and crop improvement, offering a promising avenue for developing more resilient, nutritious, and sustainable agricultural systems in the future.

IV. SYNTHETIC BIOLOGY FOR CROP IMPROVEMENT

Synthetic biology and bioengineering offer promising avenues for innovation and improvement in agriculture. These fields involve the development and modification of new biological species as well as the transformation of existing ones for beneficial purposes. Synthetic biology and bioengineering techniques can be used to enhance crop traits and plant health such as yield, nutritional content, and stress tolerance. The microbes those present in the soil has also become a crucial element that assists plants develop systemic resistance. By introducing or modifying specific genes in crops and microbes, scientists can improve photosynthetic efficiency, enhance disease resistance, optimize nutrient utilization, and develop crops species with specific traits (Pinedaet al. 2017).Another of the greatest threats to crop production is drought. It has been suggested that certain microorganisms found inside plant roots have ability to enhance tolerance against drought stress (Ngumbi and Kloepper 2016).According to reports, halo-tolerant rhizobacteria increase the resistance of microbial communities against salt stress, which in turn improve plant development and stability in unfavorable environments (Yuan et al. 2016).

Approaches of bioengineering can also be utilized for environmental remediation in agriculture. Genetically engineered crops can efficiently absorb and metabolize pollutants from the soil, water, or air, aiding in the cleanup of contaminated agricultural sites. This can help mitigate environmental pollution and restore ecosystem health.Synthetic biology enables the development of novel agricultural inputs, including biofertilizers, biopesticides, and biostimulants (Heuer et al. 2017). Through the engineering of microorganisms, scientists can design beneficial microbial communities that enhance nutrient availability, suppress pests and diseases, and promote plant growth. These biological inputs can reduce reliance on synthetic agrochemicals and contribute to more sustainable farming practices. Synthetic biology can also contribute to sustainable bioenergy production in agriculture. Engineered microorganisms can be designed to efficiently convert plant biomass into biofuels, such as bioethanol or biodiesel. This helps reduce reliance on fossil fuels, promotes renewable energy sources, and contributes to a more sustainable energy system.

Synthetic biology is used for crop improvement by applying advanced genetic engineering techniques to improve plant traits for better agricultural results. This technique involves designing or engineering organisms and metabolic pathways within plants to achieve desired characteristics. However, Synthetic biology provides great potential for crop improvement, but it also faces several challenges that need to be mitigated for successful and responsible implementation. To effectively apply synthetic biology for crop improvement, researchers need a deep understanding of plant biology, genetics, and molecular mechanisms. As well, it's important to adopt a smart and responsible approach that is supported by scientific data and standard considerations to ensure that synthetic biology applications for crop development benefit agriculture and society while reducing risks.

V. PLANT MICROBE INTERACTION TO IMPROVE AGRICULTURE

Engineered microbes hold great potential for improving soil fertility and enhancing plant-microbes interactions in agriculture.These interactions offer promising avenues for sustainable crop improvement, reducing reliance on chemical inputs and promoting environmentally friendly agricultural practices. Integrating these interactions intocrop management strategies can contribute to improved yield, quality, and resiliencein agricultural systems. (Bravo and Soberón2023).Plant-microbe interactions play a significant role in crop improvement by influencing plant health, nutrient uptake, disease resistance, and overall productivity.

To improve the growth of crops and control pests, agricultural productivity has been improved by raising the quantity of modified ffertilizers, herbicides, and pesticides. This has resulted the higher yields and good-quality foods (Loiseleur 2017). When it comes to bacteria-based insect infections, *Bacillus thuringiensis* (Bt) has been the most effective bio-insecticide for the control of various pests that belong to the lepidoptera, coleoptera, or diptera (Pardo-López et al. 2013). Bt-based pesticides are employed in both intensive agriculture and organic farming to protect a variety of crops, including cruciferous vegetables, cotton, corn, and soybeans (Bravo and Soberón2023).

Plant growth-promoting substances including phytohormones, vitamins, and enzymes can be synthesized by engineering microorganisms to enhance plant growth and crop yield. These microbes canimprove nutrient uptake and increase plant tolerance to various environmental stresses (Xie et al. 2017) including drought, salinity, extremes temperature, and heavy metal toxicity. These microbes can produce stress-protective compounds or activate stress response pathways in plants, improving their ability to withstand challenging growing conditions (Zhou et al. 2016).In the past century, long-lasting, toxic chemical pesticides have been replaced with less-permanent, low-toxicity insecticides to reduce the harm exposure to these chemicals does to both human health and the environment(Pardo-López et al. 2013).

In order to ensure the storage and utilization, it is important to develop the microorganisms and make them on a wide scale. The difficulty of creating effective formulations vary among different microorganisms. In the cases of viruses and fungi, maintaining the microbes' life is crucial. (Behle&Birthisel, 2014).Microbial communities are complex, and their interactions with plants and the environment are not fully understood. To understand the elaborate mechanism of plant microbe interaction including the factors that influence colonization, nutrient exchange, and communication, there is a input of comprehensive research is required (George et al. 2019). Advancements in high-throughput sequencing, omics technologies, and bioinformatics can help to unravel the complexity of microbial communities and their functions.

Engineered microbes need to be stable and persist in the target environment to exert their intended effects. Challenges arise in maintaining engineered traits over time and ensuring the persistence of beneficial microbial populations. The cost of developing, producing, and delivering engineered microbes can be a barrier, particularly for people in rural communities.Approaches like gene protection, optimization of microbial colonization and survival mechanisms, and monitoring and management of introduced populations can enhance the long-term stability and persistence of engineered microbes.

VI. OMICS TECHNOLOGY FOR CROP IMPROVEMENT

Omics technologies have revolutionized agriculture and crop improvement by providing powerful tools for studying the molecular components and processes within plants (Yuan et al. 2008). These technologies enable researchers to analyze and understand the genetic, epigenetic, transcriptomic, proteomic, and metabolomic profiles of crops, leading to valuable insights into their biology and potential for improvement.A wide range of “omics” techniques are fast evolving that result in improved crop plants that can tolerate abiotic stress (Chawla et al. 2011).

Omics technologies generate vast amounts of data, and their integration and analysis require advanced computational and statistical methods. By harnessing the power of Omics technology, researchers can gain a deeper understanding of crop biology, identify key genes and pathways, and accelerate crop improvement efforts for enhanced productivity, stress tolerance, and nutritional content. These technologies have revolutionized crop improvement by providing valuable information into the molecular mechanisms regulating plant traits and responses to environmental stimuli. Genomics is the study of an organism's entire DNA sequence, which includes the identification and characterization of its genes and their variations. Genome sequencing and assembly allow researchers to decipher the complete genetic makeup of crops.

Transcriptomics deals with the analysis of the whole sequence of RNA molecules (transcriptome) in a cell or tissue at a specific time(Le et al. 2012).RNA sequencing (RNA-seq) enable researchers to quantify and characterize gene expression patterns under different conditions, developmental stages, or stress responses(Chen et al. 2002). Transcriptomics helps identify key genes involved in desirable traits and reveals the molecular mechanisms underlying those traits.Proteomics involvescomprehensive analysis of the entire set of proteins (proteome) expressed in a cell or tissue (Subudhi 2011). Techniques such as mass spectrometry and protein microarrays allow researchers to identify and quantify proteins in different conditions. Proteomics helps in understanding the functional aspects of genes and provides insights into the complex molecular interactions and pathways that govern plant development, physiology, and stress responses.

Metabolomics focuses on the comprehensive analysis of metabolites present in a cell or tissue(Deshmukh et al. 2014).Metabolites are the products of biological processes, and they can provide the information aboutthe physiological status of the plant. Metabolomics can help identify metabolic pathways associated with desirable traits, assess the nutritional quality of crops, and reveal how crops respond to environmental changes and stress.Comparative genomics helps in understanding genetic variation and evolutionary relationships between different crop species and their wild relatives. Genome-wide association studies (GWAS) and quantitative trait loci (QTL) mapping facilitate the identification of genes associated with specific traits, providing targets for crop improvement through breeding or genetic engineering (Peleman and Voort 2003).

Omics technologies generate vast amounts of data, and bioinformatics plays a important role in managing, analyzing, and integrating this information. Advanced computational tools and databases are used to interpret omics data, identify candidate genes, and predict gene functions. Data integration across different omics levels can lead to a holistic understanding of crop biology and facilitate targeted crop improvement strategies.

VII. BIOINFORMATICS FOR AGRICULTURAL ACTIVITIES

Bioinformatics plays a vital role in crop improvement by computational and data analysis tools to analyze and interpret biological information related to crops. It encompasses a wide range of techniques and applications to enhance our understanding of crop genetics, genomics, transcriptomics, proteomics, and other omics data. According to the analysis above, computer based technology has been successfully used to prevent and manage agricultural disease and pests. Its primary advantages are its high efficiency, excellent accuracy, and low cost.

The yield, quality, utilization of resources, and eventual financial advantages of agricultural production are all dependent on the healthy crops production (Culman et al. 2017). As we are aware about weeds, they are considered to be harmful plants in agriculture field. Weeds are recognized in agronomy as potentially damaging plants. To detected and eliminate weeds, the agricultural sector needs to advance (Tian et al. 2020). Therefore, it is important to develop stable and secure connected systems. Related datasets may be established for the use of hyperspectral methods and deep learning neural networks in multitask fusion(Khan et al. 2018).

Prevention and management of crop diseases, insects, and weeds are essential for producing high-quality, unpolluted agricultural products and cultivating high yields. Making use of all available agricultural controls to detect pest and disease occurrences as fast and precisely as possible (Ma et al. 2019). There are few challenges with the traditional management techniques for agricultural plant protection, including a lack of attention, low precision, and a lack of timeliness (Ramcharan et al. 2019).It is difficult to reduce crop damage brought on by disease, but by using computer vision technology, prevention and control techniques have become much more timely and accurate, and it is now much easier to control crop diseases, pests attacks, and weeds growth. Early detection and preventionof diseases may reduce losses, and support long-term agricultural growth Akramet al. 2017). The advantages of computer-based technology includelimited error, great efficiency, high security, and the ability to be dynamically and continually studied. The associated approaches still have their limitations, and it will take a lot of work in the future to achieve adaptability and stability in a variety of complex circumstances.

VIII. NANO TECHNOLOGY FOR SUSTAINABLE AGRICULTURE

Nanomaterials have emerged as effective tools for the targeted delivery of fertilizers and pesticides in agriculture. These nanomaterials possess unique properties that allow for controlled release, enhanced efficacy, reduced environmental impact, and improved resource efficiency.Nanomaterials can be designed to encapsulate fertilizers or pesticides, enabling controlled release over an extended period. This controlled release mechanism ensures that nutrients or active ingredients are released gradually, matching the crop's needs and reducing nutrient loss or chemical runoff(Kah et al. 2018). It enhances the efficiency of nutrient and pesticide utilization, reducing waste and environmental contamination. For example, when herbicides were compared alone, the poly (epsiloncaprolactone) nanocapsule-based encapsulated herbicides were more toxic to *Daphnia similis* and less hazardous to *Pseudokirchneriellasubcapitata* and *Prochiloduslineatus*(Andrade et al. 2019; Clemente et al. 2014).

Nanomaterials can be functionalized to target specific plant tissues or pests. By modifying the surface properties or incorporating targeting ligands,we can design nanocarriers to deliver selective fertilizers or pesticides to desired plant organs and pest-infested areas.Recent studies have proven the effectiveness of nanosilica to reduce pests in stored grain products (Gamal 2018).Nanomaterials can also improve the solubility and stability of poorly soluble fertilizers or pesticides. By encapsulating these compounds within nanocarriers, their dispersibility and solubility in water can be enhanced(Van Aken 2015).This ensures better absorption and utilization by plants, reducing the amount of agrochemicals required for effective treatments. By reducing the amount of chemicals released into the environment, nanomaterials help mitigate pollution, soil degradation, and water contamination. This targeted delivery also minimizes off-target effects, reduces chemical exposure, and enhances the effectiveness of crop treatments.(Abigail and Chidambaram 2017).It promotes sustainable agriculture practices by reducing the ecological footprint of agrochemicals.

The nanoparticles may inhibit seed germination, slow down plant growth, and sometimes even kill plants (Yang et al. 2017). The safety and potential environmental impacts of nanomaterials need to be thoroughly evaluated. It is crucial to assess their toxicity and stability in the environment to ensure their safe use and minimize unintended consequences (Siddiqui et al. 2015).Nanomaterial-based delivery systems should be integrated into sustainable farming practices. Assessing their compatibility with organic farming, conservation agriculture, and other sustainable approaches is important to ensure their alignment with broader agricultural sustainability goals (Kah et al. 2019).

IX. RNA INTERFERENCE (RNAI) FOR CROP IMPROVEMENT

RNA interference is a powerful tool in molecular biology that has significant potential for agricultural applications and crop improvement. RNAi is a naturally occurring biological process in which small RNA molecules inhibit the expression of specific genes. This process can be used to target and regulate the expression of genes of interest in plants, making it a valuable technique for agricultural research and crop development. By targeting specific genes in the pests or pathogens that are harmful to the crops, scientists can create genetically modified plants that produce small interfering RNAs (siRNAs) (Farook et al. 2019). These siRNAs can interfere with the expression of essential genes in the pests or pathogens, effectively killing or inhibiting their growth and reducing the need for chemical pesticides (Xieet al. 2020).By targeting a gene that is essential for the mite's survival, researchers were able to significantly reduce the number of mites in wheat fields, leading to reduced transmission of viruses.RNAi can help to develop crops that are more resilient to environmental stresses, such as drought, salinity, or extreme temperatures (Macfadyen et al. 2018).

RNAi can be utilized to control weeds, which can be significant competitors with crops for resources. By developing genetically modified crops that produce siRNAs targeting essential genes in weeds, it may be possible to suppress weed growth while leaving the cultivated plants unaffected.Instead of using synthetic chemical pesticides, RNAi-based biopesticides can be developed. These biopesticides are specific to the target pests and have no negative impact on beneficial organisms or the environment (Wang et al. 2018).

Genetically modified organisms have faced regulatory hurdles and public resistance in some regions. To overcome this challenge, transparent and rigorous risk assessment studies should be conducted to demonstrate the safety and environmental benefits of RNAi-based crops.The effectiveness of RNAi can vary between different crop varieties and target organisms. It is crucial to optimize the design and delivery of RNAi molecules for each specific crop and pest/pathogen combination (Krishna et al. 2022). It's important to note that while RNAi technology holds great promise for agriculture and crop improvement, there are also regulatory and public acceptance considerations when it comes to genetically modified organisms in agriculture. Customized RNAi approaches and extensive testing on diverse genetic backgrounds can help overcome this challenge.

X. CONCLUSION

This book chapter provides a comprehensive overview of the applications and impacts of agricultural biotechnology in crop improvement and sustainable agriculture. Additionally, it addresses regulatory frameworks and public perceptions surrounding GMOs, emphasizing the importance of safety assessments and risk management. By discussing gene editing, synthetic biology, nanotechnology, precision agriculture, and nutritional enhancement, the chapter emphasizes the potential of these approaches to address global challenges related to food security and environmental sustainability. The chapter also discusses the role of precision agriculture and digital technologies in optimizing resource utilization. While the potential of agricultural biotechnology is vast, it is crucial to address ethical, social, and regulatory considerations to ensure responsible deployment and maximize its benefits for food security and sustainable agriculture.

This chapter highlights, how biotechnology contributes to enhanced crop productivity, disease resistance, and environmental sustainability. This book chapterprovides an in-depth exploration of the future directions of agricultural biotechnology, showcasing emerging technologies and advancements that hold promise for sustainable and resilient food production. Overall, this chapter serves as a valuable resource for farmers, researchers, organizations and industries interested in the field of agricultural biotechnology. Additionally, it underscores the importance of responsible innovation, considering ethical, social, and regulatory aspects for successful implementation.

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