From Plant Health to Food Quality and Environmental Protection: The Role of Modern Biotechnology Techniques in Supporting Sustainable Food Security

Editors

Burair Ahmed Nasir Gamaz
University of Karbala College of Agriculture Department of Plant Protection Specialization: Plant Pathology

Aqeel Hayder Atallah
University of kerbala college agricultural Department of Food Science Specialization: biotechnology

Nawres Mohsin Abbas Salman
University of Kerbala College of agriculture Department of plant protection Specialization: Plant protection

Saja Diwan Jasib Abd
University of Karbala College of Agriculture Department of Field Crops Specialization: Field Crops

Doaa Talib Mohammed Shabib
Al_Qasim Green University College of Environmental Sciences Department of Environmental

AkiNik Publications ®

New Delhi

Published By: AkiNik Publications

AkiNik Publications
169, C-11, Sector - 3,
Rohini, Delhi-110085, India
Toll Free (India) – 18001234070
Phone No.: 9711224068, 9911215212
Website: www.akinik.com
Email: akinikbooks@gmail.com

Editors: Burair Ahmed Nasir Gamaz, Aqeel Hayder Atallah, Nawres Mohsin Abbas Salman, Saja Diwan Jasib Abd and Doaa Talib Mohammed Shabib

Publication Year: 2026

Edition: 1st

Pages: 112

Paperback ISBN: 978-93-7150-173-6

E-book ISBN: 978-93-7150-038-8

Book DOI: https://doi.org/10.22271/ed.book.3528

Price: ₹ 555/-

Registration Details

- Printing Press License No.: F.1 (A-4) press 2016
- Trade Mark Registered Under
    - Class 16 (Regd. No.: 5070429)
    - Class 35 (Regd. No.: 5070426)
    - Class 41 (Regd. No.: 5070427)
    - Class 42 (Regd. No.: 5070428)

Contents

Abstract

Food security is currently under threat from a misalignment between food demand and supply, which is further exacerbated by population growth, changing dietary habits, the diversion of grain for fuel, and the effects of climate change. Food insufficiency, hunger, and widespread poverty exist alongside post-harvest losses and malnutrition, which have serious public health implications. Addressing these challenges requires targeted interventions that increase the productivity of agriculture and food systems while sustaining their broader functions. Modern biotechnology techniques can play a leading role in this effort by extending beyond the classic approach of improving resistance to biotic and abiotic pests and stresses and embracing a much broader agenda that encompasses food quality and safety, better resource-use efficiency, and environmental protection.

Biotechnology-based innovations offer the potential to be transformative. Nevertheless, it is vital to recognize that these products will not all lead to genuine revolutions in food production and that many will have effects similar to those achieved through traditional breeding or management practices. Proper oversight, including governance of the research and development process, is essential to ensure that these technologies are used wisely and that their benefits can be exploited safely. Emphasis on genetic engineering and genome editing in this context is warranted by the growing public discourse surrounding current research directions and the safety of these developments for human health and the environment.

Chapter - 1

Introduction to Sustainable Food Security and Biotechnology

Food Security and Nutrition Security: Understanding the Concepts and Interrelationships

Food security exists when all people at all times have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life. The term food security encompasses a range of dimensions—access, availability, utilization, stability—and captures the notion that food systems are shaped by politics, power relations, and, ultimately, institutions. Food security is thus an outcome with close ties to processes of economic growth, income distribution, and poverty reduction. It is a long-term goal of national and regional economic development stemming from decisions made by cultural, social, and political authorities. Food security is not achieved only on the diet side; the requirements for production, processing, transport, storage, distribution, and consumers consuming food are also taken into account.

The concept of nutrition security encompasses food security as well as an adequate health and sanitation environment, an adequate level of education, and adequate care. Many people may have access to a rich, varied, and nutritious food supply but are still malnourished. These malnourished groups are among the poorest of the poor and are usually deprived of all the other conditions for nutrition security [1, 2, 3].

Global challenges in food security

Sustainable food security remains one of humanity's greatest challenges. Despite enormous increases in food production from traditional agricultural and livestock practices, an unacceptably high number of people are undernourished. More worrying is the lack of recent progress in food security. The United Nations Food and Agriculture Organization estimates that there are 811 million undernourished people in the world today. More than 41 million people in 43 countries face life-threatening food shortages, according to the World Food Programme. Above all, the most vulnerable groups, particularly women and children, are seriously affected. Food production is permanently vulnerable to climate change, more specifically to drought, the most critical constraint to food security.

The intensified use of improved technologies had been found to have a significant positive impact on productivity of field crops in India, but the process remains incomplete and uneven. Recently, the demand for agricultural products has surged due to the explosion process of Corona, and the supply, unfortunately, has not been commensurate. Even though agriculture and allied sectors have been specifically earmarked for development during the last six decades and have shown significant progress and need to be further supported, the country's food and nutritional security has yet to be achieved [4, 5, 6, 7].

Evolution of agricultural biotechnology

Agricultural biotechnology encompasses a range of experimental and harnessed biological processes used in product development. Techniques include classical selective breeding of plants and animals, hybridization, and biotechnological processes like plant tissue culture and recombinant DNA technology. Informing risk assessment, regulation, and public policy have evolved in pace with biotechnology as it has advanced, matured, and been implemented. Global adoption patterns have began to favour crops with traits that specifically benefit the environment and the people of developing countries. Modern agricultural biotechnology is driven by the convergence of several technologies that tackle some of the most pressing issues of our time, the main ones being climate change and sustainable food security. In this regard, encompassing all aspects of the food chain, from the production of primary crops and ingredients and food safety to food and nutrition security, genetic control of post-harvest losses, the mitigation of agrochemical pollution, and the treatment of food-related illnesses.

Modern biotechnology techniques have played a vital role in increasing agricultural production over the past two decades and will continue to do so well into the future. Nevertheless, areas of limited progress remain, especially when it comes to producing crops that are resilient to climate change or are improved from a nutritional perspective for specific segments of the population. Addressing these requirements will also help to advance many of the SDG targets and indicators. Future innovations are expected to arise from recent breakthroughs in molecular biology and those in big data, artificial intelligence, and the digital economy. Such ingenious new revolutions will continue to offer opportunities for technology transfer to developing countries. However, providing effective risk management frameworks, helping farmers to adapt to changing climatic conditions, and improving public perceptions and trust will be vital for the future needs and attitudes of biotechnology adoption [8, 9, 10].

Link between plant health and food systems

Plant health is a vital component of food systems because healthy plants support high yields, ensure the delivery of adequate nutrients, and help crops resist stresses that can threaten production levels. Yet, crop diseases and pests cause widespread damage leading to severe yield losses, quelling the supply of safe and nutritious food. Certain key diseases account for vast annual losses, and climate change is exacerbating threats from pests and pathogens. Consequently, plant health management is a prerequisite for achieving food security.

Ensuring plant health hinges on effective prevention and mitigation. A diverse array of biotic and abiotic factors can adversely affect plants: in addition to diseases and pests, drought, salinity, flooding, and climate change all pose serious threats to food production. Plant health management seeks to sustain or improve plant health and productivity by enhancing resistance to biotic and abiotic stresses, thereby fostering food security and improving food safety. Cultivation of resistant varieties is a key approach for combating diseases, and the development and release of crops with improved resilience to major stressors is a high priority for both scientists and farmers. Integrated strategies that combine cultural, biological, and genetic methods can provide even greater protection. Systematic monitoring of diseases and pests is also essential [11, 12, 13].

Biotechnology in sustainable development goals (SDGs)

The relevant Sustainable Development Goals (SDGs) and associated targets and indicators strongly support the application of biotechnology in crop improvement and development. Among these, SDG-2, which aims to end hunger and achieve food security, is most directly linked to biotechnological progress in ensuring food safety, quality, and availability; enhancing resource use efficiency; and protecting crop plants from biotic and abiotic stress. Other targets, such as reducing post-harvest loss and achieving food security and sustainable agriculture, further emphasize the relevance of biotechnology.

SDG-3, addressing good health and well-being, includes targets related to the reduction of healthy life expectancy due to communicable diseases and premature mortality from these diseases. Such diseases are often transmitted through food contaminated by microbial pathogens, endorsing the need for molecular tools for food safety testing and detection. SDG-12, which aims to ensure sustainable consumption and production patterns, features a target to substantially reduce waste generation, addressing the development of protective physical barriers to control post-harvest microbial contamination and spoilage. SDG-15, promoting the sustainable management of forests and halting biodiversity loss, encompasses targets related to combating soil biodiversity loss [14, 15, 16].

Future perspectives of agri-biotechnology

Limitations in the application of plant science and biotechnology have decreased. Innovations in these fields can now be implemented in a variety of crops, translated across species, and made publicly available. The coming years should see an unprecedented spectrum of impactful inventions in these areas. Criteria commonly defining revolutions in the area of crop improvement—such as a reduction of the burden of the major production diseases and pests, or enabling stress tolerance, thereby stabilizing crop production in the face of climate change—should almost certainly be met, and likely surpassed.

The anticipated wave of inoculation against the major production diseases of plants could be achieved by employing breakthroughs in repair mechanisms in DNA. Evidence already indicates major repair components performing naturally, and numerous natural forms and even common laboratory strains of host-specific pathogens that contain hypersensitive response elicitors therefore conducive to such multifactorial resistance. These varieties should indeed pass testing and approval with respect to environmental impact, as the major pathogens will remain present but depleted in virulence by the introduction of resistance traits. These advances in crop improvement will be dynamic since incorporating even partial resistance into resistance-susceptible crops will be easily achievable, leading not only to the well-known UAV technology surveillance of population dynamics but also to programming dissemination within a genomic framework.

The anticipated wave of inoculation against the major production diseases of plants could be achieved by employing breakthroughs in repair mechanisms in DNA. Evidence already indicates major repair components performing naturally, and numerous natural forms and even common laboratory strains of host-specific pathogens that contain hypersensitive response elicitors therefore conducive to such multifactorial resistance. These varieties should indeed pass testing and approval with respect to environmental impact, as the major pathogens will remain present but depleted in virulence by the introduction of resistance traits. These advances in crop improvement will be dynamic since incorporating even partial resistance into resistance-susceptible crops will be easily achievable, leading not only to the well-known UAV technology surveillance of population dynamics but also to programming dissemination within a genomic framework [17, 18, 19].

Chapter - 2

Plant Health and Crop Productivity

Plant health and crop productivity are critical components of the broader food system. Plant health is defined as the state wherein a plant is free from diseases, pests, injuries, or any condition that interferes with the functioning of vital processes. A healthy plant is capable of withstanding diseases, pests, and abiotic stresses such as drought or salinity and is not a source of infection for other plants. High plant resilience ensures the sustainable production of safe, nutritious food while conserving the environment and natural resources. Plant health management aims to create conditions for plant growth that are conducive to preventing disease, pest, or abiotic stress-induced yield losses. Apart from cultural practices, biological control of diseases and pests, and regular and careful monitoring of diseases, pests, and abiotic factors can be integrated with the genetic manipulation of crops for developing traits that provide greater resilience and the ability to sustain yield under critical levels of biotic or abiotic stresses.

Healthy plants supply nutritious food for people and animals. The World Health Organization estimates that about 2 billion people suffer from micronutrient deficiency, also known as hidden hunger. The Food and Agriculture Organization projects that by 2025 there will be a need for a 70% increase in food production to meet the demands of the expected population of more than 8 billion people. It is also expected that with climate change, plant disease pressure will increase by about 10%-25%, which could further compromise food security. Estimates suggest that an annual loss of about 25% of total crop yield occurs due to diseases. The total annual loss due to major plant diseases has been calculated at US$220 billion. Thus, the application of biotechnology to manage plant health will play a vital role in increasing crop productivity and quality and helping supply food for the ever-growing population [20, 21, 22].

Concepts of plant health management

Plant health, akin to human health, is vital for optimal yield and quality. Resilience defines a plant's capacity to tolerate or recover from stress. Diseases and pests, unpredictable biotic factors, can be mitigated through cultural management. Abiotic stressors are more certain, but prevention remains challenging. Increasing research on the molecular mechanisms of infection may enable future genetic control. Timely implementation of integrated plant health management helps achieve record productivity.

Plant health promotes withstanding pests and diseases in a preventive manner, encompassing cultural, biological, and genetic approaches. A well-maintained ecosystem lowers vulnerability. Engineered plants with resistant traits may tolerate pathogen loads, while healthy plants often yield and resist better. Global food loss and wastage are abundant, and about 30% of potential production is lost annually. Plant disease-induced yield losses are significant: ~25% for major crops and ~30–35% for economically important crops. Such consequences invite research in plant pathology, focusing on detection and management to prevent damage [23, 24, 25].

Biotic and abiotic stress factors

Plants endure a range of biotic stresses caused by pathogens (viruses, bacteria, nematodes, fungi, and their products) and pests (insects, arachnids, and nematodes). The connection between crop disease and food security is striking, as pathogens account for billions of dollars in annual global yield losses—nearly 20% of potential food production. Major infectious diseases in crops (both cultivated and orphan) are well established, and pathogens are monitored closely, making them prime candidates for disease-resistance strategies. Sustained efforts in elucidating the plant immune response and the molecular mechanisms underpinning pathogen virulence have facilitated the development of disease-resistant crops. Several crops have been genetically engineered with single-molecule resistance genes and deployed, with population-level effects on disease management.

In addition to biotic threats, plants also face abiotic stresses such as drought, salinity, extreme temperatures, and flooding. Drought conditions induced approximately 70% of the area under global food production. Although certain areas may witness enhanced rainfall, increasingly erratic precipitation patterns intensify the incidence of drought and flooding. Besides global warming, ocean thermal stimulation is projected to endanger agriculture in hitherto less affected areas. The ability of mollisols, aridisols, and vertisols to withstand climatic aberrations is failing, leading to soil degradation. There has been a concerted effort to develop drought-, salinity-, and flooding-tolerant crops over the past few decades through traditional breeding and genetic engineering [26, 27, 20].

Yield losses due to plant diseases

Globally, major crop diseases are estimated to cause a loss of 20–40% of potential yields. In terms of food security, the economic loss caused by various diseases is valued at □90,600 crores annually. Crop plants are attacked by a myriad of diseases caused by bacteria, fungi, nematodes, mollicutes, phytoplasmas, viruses, and viroids, as well as invasive alien species. A few diseases such as blight of rice, yellow rust of wheat, wilt in pulses, downy mildew in millets, and late blight of potato have been well documented as widespread in India and causing significant losses.

It is also a well-documented fact that food security in terms of food availability and access (availability to everyone), food utilization and nutrition, and region and time-wise stability against the many natural and man-made disasters are the greatest challenges that mankind faces. The technological input for augmenting food visibility should include the development of crop species that are high yielding, resistant/tolerant to biotic and abiotic stresses, rich in nutrients, and suitable for risk-prone areas. Increasing crop yield by ensuring healthy plants is essential to meet the challenge of food scarcity and provide safe crops for food security. Therefore, an integrated approach combining agronomic and biological strategies along with the newer biotechnological tools will be the key for progressive, sustainable and eco-friendly crop production [28, 29, 30].

Role of biotechnology in enhancing productivity

Crop productivity is negatively impacted by biotic and abiotic stresses exerted directly or indirectly on plants, leading to major yield losses worldwide. Management strategies that prevent diseases caused by pathogens and pests can contribute considerably toward reducing these losses. Both responsive and tolerant traits against various pathogens and pests can be engineered or introgressed into crops to protect them from damage, ultimately enhancing crop yield. Resilient plants can also mitigate the impacts of a changing climate and improve productivity in an environmentally sustainable manner. Therefore, integrating plant disease management, pest management and abiotic stress management strategies into production plans is critical to achieving higher yields.

Plant–pathogen interactions cause losses that can endanger food security; biotechnology offers solutions for detection and management. Both the hidden and visible impacts of diseases on yield increase the vulnerability of food systems. Losses caused by potato late blight (Phytophthora infestans), wheat rusts, rice blast (Magnaporthe oryzae), yellow rust, downy mildew of pearl millet, and stem gall of mustard are highlighted. Factors affecting adoption of biotechnology-based solutions are also discussed, as effective management will enable growers to transgress yield ceilings and obtain sufficient food of adequate quality [31, 32, 24].

Integrated plant health strategies

Increasing knowledge and understanding of the complex relationships between plants and their environment can help improve crop productivity. The development of crop varieties that combine various approaches, coupled with better cultural practices, will ultimately contribute to improved yields and quality while minimizing the costs associated with plant health and environmental protection.

A plant health management strategy based on cultural practices may include water and nutrient management, sanitation, crop rotation, resistant varieties, release of natural enemies, proper timing of sowing, weed management, and other practices. These measures depend on the careful evaluation and analysis of environmental conditions and pest status and should be integrated into a management program. Detection of biotic and abiotic stresses at the right time is essential for successful plant health management. Monitoring systems based on remote sensing can play a key role in providing timely information about stress status and changes. Plant health management utilizing biological, cultural, and genetic approaches in a judicious manner can minimize loss of production in a sustainable way, thereby improving crop yields, quality, and food security [33, 34, 35].

Chapter - 3

Molecular Plant Pathology

Molecular Plant Pathology: Mechanisms and Tools

Plant disease resistance is a component of plant health that is essential for higher crop productivity, food security, and safety. Understanding plant–pathogen interactions at the molecular level enables the identification of disease resistance genes and their deployment through breeding, molecular breeding, and biotechnological approaches. The mechanisms of plant immunity, especially the recognition of pathogen-associated molecular patterns and the activation of downstream defense responses, are fundamental for engineering the resistance trait by activating such pathways. Advances in pathogen detection technologies using molecular tools contribute to developing management strategies.

Most plants are attacked by a variety of pathogens, including viruses, bacteria, fungi, and nematodes, which have the potential to cause significant economic losses both directly through crop yield decreases and indirectly through increased production costs for disease management. The concept of integrated disease management includes but is not restricted to the avoidance, tolerance, and damage-limiting approaches. Genetically modified plants with disease resistance have been developed and cultivated in many countries around the world. The advancements in gene cloning and sequencing technologies have paved the way for a better understanding of the molecular mechanisms of plant immunity and disease resistance. Pathogen detection technologies have also developed rapidly, enabling the design of detection systems with high specificity and sensitivity applicable in the field.

A thorough understanding of the recognition and signaling processes involved in plant–pathogen interaction is imperative for further advancing this aspect of plant health. Recognition of the different types of pathogens— viruses, fungi, bacteria, and nematodes—elicits a complicated signaling network that regulates the plant's defense responses. Extensive efforts have been made to elucidate the molecular pathways involved in immunity. Knowledge gained from studying these pathways can be used to engineer enhanced resistance in important crops [36, 37, 38].

Plant–pathogen interactions

Are the molecular and cellular processes that take place during an encounter between plants and pathogens. These interactions must be understood to effectively utilize biotechnological tools for disease management. A successful interaction requires recognition of the pathogen by the plant and subsequent activation of defense mechanisms in the plant. Pathogen virulence factors may suppress or modify plant recognition and the ensuing responses. Recognition is a highly specific process in which the plant perceives pathogen-associated molecular patterns (PAMPs) or elicitors secreted by the pathogen. Effectors introduced into the host by the pathogen, which may even be of host origin, can weaken or bypass recognition. Various receptors and signaling pathways in the plant contribute to recognition. After recognition, a cascade of phytohormonal signaling usually activates defensive processes like localized cell death, the hypersensitive response (HR), and systematic acquired resistance (SAR).

Plants have evolved a general response to biotic stress with a cytokinin-controlled developmental switch contributing to the balance between immunity and growth. Salt-induced osmotic stress enhances host susceptibility to foliar fungal pathogens. Nitric oxide can have opposing roles in systemic and local defense responses in plants. Energy-limited plants form non-specific resistance-gene-dependent defenses against biotrophic pathogens. Non-canonical programmed cell death regulates immunity. The antimicrobial defenses of plants also contribute to delaying or preventing disease. Recognition of pathogens and the components of pathogen recognition contribute to the immunity of the host. In the molecular armory of plants, recognition of viruses by the host with consequent downstream reactions is unique. Phytocytokines can induce various defense-related networks. Targeted metabolomic analysis uncovered the metabolic basis of susceptibility to drought in a resistant cultivar [39, 40, 41].

Molecular mechanisms of disease resistancee

In higher plants, molecular dissection of disease resistance mechanisms has unveiled critical pathways that bolster basal immunity and activate innate immune responses. Pathogen-associated molecular patterns (PAMPs) serve as initial elicitors of innate immunity. These microbiota-associated signals activate a calcium-dependent protein kinase cascade that leads to the synthesis of reactive oxygen species (ROS) to establish programmed cell death (PCD) at the site of infection. Plants possess specific disease resistance (R) genes that endow for durable resistance through the recognition of pathogen effectors, a process that activates localized hypersensitive responses (HR). A combination of R genes that target different aspects of pathogen biology shows promise for broad-spectrum disease resistance. Despite the identification of a large number of R genes, the resistance conferred by most cannot be sustained because of the evolving nature of pathogens. Such limitation can be addressed through a focus on signalling pathways that transduce defence responses toward fungal, bacterial, and viral pathogens. Another cogent strategy is to exploit quantitative trait loci (QTLs) associated with trap and neighbouring effect to increase durability. Moreover, the identification of nucleotide-binding site-leucine- rich repeat (NBS-LRR) genes that are highly co-expressed with ethylene-induced pathogenesis-related (PR) genes and control biotrophic/hemibiotrophic pathogens points to a convergence of defence pathways.

Understanding and effectively modifying the specific genes responsible for disease resistance is crucial for addressing the challenges posed by rapidly evolving pathogens. Several research groups are using RNA interference (RNAi) technology as a means of combating plant pathogens that are associated with enhanced virulence and lowered virulence in target hosts or affect several different plant species. Modifications to the disease-causing genes have been produced not only through RNAi but via other biotechnology-based solutions. In the case of Fusarium wilt disease, commercially important brinjal (eggplant) varieties with Fusarium-wilt resistance have recently been developed through integrated methods that combine silencing the pathogen-encoding gene with transgenic approaches, multilocation trials, and collaborations across institutions [42, 43, 44].

Host resistance genes

Induce immunity in host plants against invading pathogens. Knowledge on several resistance (R) genes has been delivered through the gene-for-gene hypothesis, which stipulates that a pathogen Avr gene recognizes the corresponding R gene's product and this recognition activates the defensive response in the host. The R gene family acts as a major player in plant defence by specifically recognizing the matching effector present in the invading pathogen, triggering an accelerated hypersensitive response through a signal transduction cascade and ultimately conferring immunity. General immunity against broad-species pathogens is governed by the operation of multiple QDR loci other than R genes. The deployment of confirmed major R genes provides effective, stable, and economical disease control under optimal biotic stress conditions.

A large number of R genes have been identified in major crops having importance in plant pathology. The grapevine R genes against numerous diseases such as powdery mildew, downy mildew, grey rot, black rot and crown gall have been identified. R genes participating in the interaction of peach, pepper, tomato and almond with different pathogens have been detected. The role of R genes in wheat- wheat leaf rust, wheat- barley stripe mosaic virus and rice- bacterial blight interactions has been discussed recently. R genes have provided durable, effective and economical control of plant diseases in crop production, and facilitated selection for resistance through marker-assisted breeding [45, 46, 47].

Pathogen detection using molecular tools

Recent advances in molecular biology have facilitated the detection of pioneering infectious diseases of crops at various growth stages. Different forms of simple and sophisticated molecular markers have been developed, allowing the detection of several invader organisms in diverse types of complex plant materials in the field. Newer molecular tools such as real-time polymerase chain reaction, loop-mediated isothermal amplification, DNA microarrays, and next-generation sequencing are emerging for sensitive diagnostic detection and identification of phytopathogens. Such technology aids in the detection and quantification of plant diseases at early stages, helping in the appropriate management of crop diseases and ensuring world food security.

Increasing global food demand due to rising population pressure has exacerbated the biotic and abiotic stress factors threatening crop production. Plant pathogens especially cause considerable economic losses in crop production, and managing them with higher precision is a global challenge. Ensuring rapid and accurate quantification of pathogens in infected plants is a necessity for minimizing crop losses. Accurate assessments of diseases can be achieved by determining the incidence of pathogens in plant samples that can serve as reservoirs and inoculum sources. Conventional methods of pathogen detection are time-consuming, labor-intensive, and sometimes unreliable for complex biological materials. Molecular approaches to the detection and quantification of pathogens can answer such challenges, providing a range of possibilities that assist in accurate disease diagnosis and management [48, 49, 50].

Biotechnology-based disease management

Besides the above-mentioned conventional methods, there are also various biotechnological techniques to manage plant diseases affecting different crops. These methods focus either on pathogen suppression or enhancing plant resistance against pathogenic organisms. The main approaches include RNA interference (RNAi), the development of genome-edited plants, and biotechnology-based interventions. RNAi, in particular, holds great promise in combating viruses and fungal pathogens since nucleic acids are the major components of these pathogens.

The knowledge gained from research in plant–pathogen interaction facilitates the development of disease-resistant plants. These diseases cause severe crop yield losses, especially in the developing world. Although traditional breeding methods remain the principal means to develop resistant crops, the advent of modern biotechnology has enabled the transfer of host resistance genes, components of the defense-signaling pathways, or other relevant genes into susceptible cultivars. These transgenic approaches are complemented by biotechnological tools for pathogen detection, a prerequisite for the effective implementation of management procedures.

Over the past three decades, the number of commercialized biotechnology-based disease-management interventions has burgeoned, and the application of these techniques has spread from crop improvement to pathogen control. The sickest plants, which are going to die, should be discarded as these are potential sources of secondary infection [51, 52, 53].

Chapter - 4

Genetic Engineering for Crop Improvement

Genetic Engineering provides an effective tool for improving crop desirable traits using a precise and defined approach. Genetic engineering principles and techniques paved the way toward the development of genetically engineered (GE) transgenic crops with desirable traits for agricultural production and sustainability. These crops have been developed for yield improvement, pest resistance, tolerance against heat and drought, salt stress, improved nutritional quality of food, and the reduction of anti-nutritional factors in food. So far, these traits have been efficiently deployed to the most important crops around the globe for farmers' profit and the consumers' health benefits.

Genetic Engineering Principles. Plant genetic engineering changed the course of agricultural crop improvement. Precise manipulation of the plant genome using synthetic genes/traits employing plant transformation protocols paved the way toward the development of genetically engineered (GE) plants with desired traits for agricultural production and sustainability in addition to traditional breeding approaches. These traits are useful for yield improvement, biotic/abiotic stress tolerance, resistance to pests and diseases, Vitamin/E-?carotene-A/iron/selenium biofortified enhancement, and reduction of anti-nutritional factors in food. Potential input characters and other associated traits have been efficiently deployed to economically important crops around the globe, leading to farm benefits of up to $228 billion worldwide by the end of 2015. Salient features of transgenic crops with improved characteristics are detailed. Knowledge of vectors, methods of gene introduction in plants, selection of transgenic plants, and biosafety aspects is essential to develop genetically modified crops with required properties.

Stress-Tolerant Crop Development. Drought, heat, and salinity stress are the major natural constraints determining plant growth and productivity. Climate-smart sugarcane is an integrated platform to develop and implement germplasm banks and selection of suitable genotypes, identification of trait-specific QTLs, markers, and genes for introgression, deployment of tolerant genotypes, identification of tolerance mechanisms, development of stress-tolerant hybrids and varietal replacement, and breeding of stress-tolerant sugarcane and other crops in association with the network institutes. Recent developments on the above aspects in relation to development of stress tolerant cucumber, tomato, potato, fruit crops, rice, wheat, sorghum, finger millet, maize, and sugarcane are highlighted [54, 55, 56].

Principles of plant genetic engineering

Plant genetic engineering refers to the stable transfer of defined genes conferring specific traits into the genome of a plant species. Molecular cloning vectors, techniques for transforming donor T DNA into recipient plant cells, suitable selection systems, and post-transformation analysis methods have been developed for many plant species. The invention of transgenic plants has led to the development of hundreds of ge-nomes modified by transfer of single or multiple genes from various sources, generated by procedures that are increasingly becoming routine.

The principle of plant genetic engineering involves the insertion of a foreign gene containing its own promoter into a defined region of the plant genome through recombination, thereby accomplishing two objectives: One is gene transfer into the host plant, and the other is deletion of unwanted DNA. Introduction of a gene in a targeted manner in close proximity to the endogenous genes providing synergistic effect improves its performance [57, 58, 59].

Transgenic crops and traits

A range of transgenic crops has already been commercialized globally, engineered for both agronomic and biotic/abiotic stress-tolerance traits. These advancements offer an opportunity to enhance productivity, particularly in regions vulnerable to the adverse effects of climate change. Other transgenic crops have aimed to improve quality by contributing to public health. Among these crops, vitamin A-enriched Golden Rice, iron-demands in staple crops, and synthetic T1D-3 in wheat have gained major attention. Additional quality-enhancing traits, such as high-temperature-tolerant starch grains or allergenic protein-free soybeans, are expected to enable efficient food production and minimize health hazards associated with food consumption.

The production of genetically engineered crops that are resistant to abiotic stresses including drought, salinity, and heat is currently regarded as the most promising approach due to the anticipated increase in the frequency and magnitude of these stresses as a consequence of climate change. Significant progress has been made in the generation and field-testing of drought- and salinity-tolerant crops. In some cases, these traits have been incorporated into elite varieties, permitting an enhanced food-security response for large regions of the world [60, 61, 62].

Stress-tolerant crop development

The growing frequency and severity of heat and drought stresses on global agriculture necessitate the development of climate-resilient crops. High temperatures can cause physiological and biochemical imbalances in plants, negatively affecting crop production, quality, and global food security. Elevated daytime temperatures may adversely affect flowering, pollen germination, and fertilization and thus yield, while hot nights can lead to higher respiration rates, reduced net carbon assimilation, early senescence, and lower yield potential. The increase of drought- and heat-induced premature leaf senescence in staple crops like wheat and rice could be detrimental during critical stages such as flowering and grain filling. In rice, water loss at the vegetative stage causes upregulation of senescence-associated genes (SAGs), resulting in yield penalty, especially when drought occurs before flowering; during flowering and grain-filling stages; and under field conditions. Overall, climate change has increased such Agronomic Critical Weather and physiologically damaged crops.

A multi-trait genome-wide association mapping approach, coupled with genomic prediction, can help enhance heat-stress tolerance in bread wheat combining with other stresses. Drought is mainly seasonally prominent in transient regions and restricts crop yield and quality globally. Hybrids of drought-tolerant cultivars and strategic mega-environments can be developed for resilient yields without holistic breeding approaches. The successful introgression of the GmHsfA4a gene into chickpea enhanced drought tolerance in the T1 transgenic lines and far-advanced backcross progeny with other associated traits. Several strategies, including synthetic tandem repeat of HSFs and miRNA-mediated manipulation of rare glucose formation in plastids, can enhance drought tolerance in plants. A novel transgenic approach is used to elucidate the effect of HsfA4 and its neighboring genes in Cucumber melo on drought tolerance. Climatically responsive flowering genes controlling early flowering in Arabidopsis under extreme heat conditions are also being used for the development of heat-resistant crops, including chickpea [63, 64, 65].

Biofortified crops

Breakfast or breakfast cereals containing GM crops biofortified with beta-carotene, iron, and zinc, or with enhanced lysine have been developed and consumed in nutrient-deficient countries. Important GM crops expected to benefit public health by increasing the level of essential minerals are cereals, sorghum, wheat, millet, rice, potatoes, cassava, and legumes. About 800 million human beings suffer from vitamin A deficiency (VAD) that can cause blindness and death, while others face iron and zinc deficiencies that hinder cognitive development and lower immune resistance. Since genetically modified crops present a faster and better genetic engineering option to develop crop varieties resistant to diseases and climatic stress, there is a need to design other staples to help reduce the Vitamin A deficiency, iron and zinc deficiency in the human population in India and other developing countries.

In addition to suffering from various kinds of nutrient deficiency, India is the largest producer of transgenic crops. Various GM crops bioengineered for the nutrition of people are presently grown in the country. For example, the papaya crop is bioengineered to inherit a gene responsible for ring spot disease resistance and is cultivated in about 20000 ha; no such disease has been reported, and the crop has won global fame as the ‘healthy papaya’. Scientists are designating other important food crops like rice, wheat, maize, sorghum, legumes, and canola so that those affected by VAD, Iron and Zinc deficiency might obtain sufficient minerals from those crops. The temperature and photoperiod effect on the flowering behaviour of various crops have been addressed. The Centre and State Governments, along with the International Food Policy Research Institute in New Delhi, have instituted a system with a group of scientists in Andhra Pradesh to evaluate GM crops and confer their view on its effectiveness [66, 67, 68].

Biosafety and regulatory frameworks

Risk assessment of genetically engineered crops has gained traction since the 1980s, leading to implementation in several developed and developing countries. Dedicated regulatory mechanisms exist in the USA, Canada, the European Union, and Asia, with procedures emerging in Latin America, Africa, and the Pacific. No biosafety laws govern genetically engineered crops in India, where oversight falls within the main Agricultural Ministry. Regulatory bodies assess proposals for large-scale trials, field tests, or commercial release of genetically engineered plants using standard release approaches for conventional crops, referencing the Codex Alimentarius guidelines on risk assessment of genetically engineered plants introduced for food and feed and for environmental release.

Protocols also cover novel types of products posing new hazards, including plants engineered with double-stranded RNA silencing, gene editing without vector insertion, and animal products from cloned animals. Risk assessment of genetically engineered plants not covered by existing protocols necessitates evaluation on a case-by-case basis. The scientific community supports the establishment of harmonized biosafety regulations for genetically engineered plants, which assure safety while fostering biotechnological innovations with minimal delays [69, 70, 71].

Chapter - 5

CRISPR and Genome Editing Technologies

CRISPR and other genome editing techniques have advanced rapidly over the past decade. New opportunities now exist for precise, rapid, and efficient crop improvement and development of new varieties, while the latest advances in RNA-guided Cas-mediated genome editing and functional genomics may also be valuable in other fields. However, precision breeding technologies, including CRISPR-Cas genome editing, raise considerable public and media interest and ethical concern. Many countries are currently reviewing plant breeding innovations and understanding how to regulate and support these emerging technologies within existing frameworks. Genome editing is a powerful tool for improving plants, addressing issues related to plant health and safe food, and providing more efficient, robust, and resilient crops. Numerous publications and research reports are available that describe the potential applications in various crops. The technology is progressing quickly through multiple applications, and evidence-based reports will increasingly provide insights into the advantages, efficiency, and risks associated with genome editing in plants.

The CRISPR-Cas system for genome editing has become a focus of interaction studies due to its simplicity and dual function as an effector and reporter. The availability of a single RNA programming unit allows for easy multiplex applications and makes testing of a large number of different target lines possible. High target specificity, low capability of random mutations, and increased detection systems to identify low-frequency off-target mutations further reduce concerns regarding CRISPR-Cas systems, while recent studies provide insight into detection and prediction of off-target effects. Recent advances in golden rice, blight resistance in cassava, omega-3 fish oil synthesis in oilseed crops, and response to pests are expected to benefit food systems and human health. However, the actual gain through genome-wide crop improvement is still highly dependent on phenotyping technologies. A comprehensive analysis of the remaining bottlenecks and needs will support the translation of these new genome-editing methods into precise and cost-effective means for crop improvement in the future [72, 73, 74].

Overview of genome editing tools

Genome editing encompasses a cluster of biotechnological techniques that allow precise modifications to the DNA of a living organism. These techniques have gained such attention because they enable genes or gene networks to be “switched on,” “switched off,” or “rewritten,” depending on the objectives. Genome editing differs fundamentally from genetic engineering and its associated techniques, which take a “transgenic” approach, i.e., these Techniques transfer genes from a donor organism into the genome of a recipient organism to confer specific traits. Nevertheless, genetic engineering is a prerequisite for most genome-editing techniques, as the components that make gene editing possible are generally first expressed in the target cell as transgenic constructs, which are then subsequently removed from the edited plants.

The two classes of products that genome editing techniques are producing in crops and other plants are products containing targeted modifications to one or both copies of a specific gene, i.e., targeted “knockouts,” or products containing nucleotide sequence changes at a specific locus, whether a “knockout” or a “knock-in” product, such as the addition of a region of DNA that alters the function of the targeted gene, or introduces a new gene or gene variation, such as a disease-resistance gene from a wild relative. Importantly, genome-editing technologies produce precisely defined changes in the plant genome. This fundamental limitation effectively alleviates concerns about uncharacterized insertion effects that regulated transgenic products have thus far been unable to overcome [75, 76, 77].

CRISPR-Cas systems in plants

CRISPR-Cas systems are the latest and most widely used genome editing tools in several organisms, including plants. Selection of an appropriate system for editing is determined by the application and delivery system of the Cas proteins along with the gRNA. The editing can be performed either by delivering the Cas proteins along with the gRNA or by introducing the genes encoding the Cas proteins with the gRNA. The editing system requires considerable expertise in several disciplines; therefore, integration with genetic engineering or other breeding strategies and phenotyping is needed for the precise development of desired traits in crops. Although gene editing is considered precise and convenient, proper consideration of off-target effects and their management is required. The public perception of novel technologies in crops demands greater responsibility from the scientific community to gain public trust and ensure accountability. Environment and health safety must also be overseen with a higher level of scrutiny in tandem with other biotechnology applications or breeding techniques. The policy of the technology must also consider public sentiments and trade aspects, aligning with the bioethical tenets of the society. The translational potential of genome editing in several crops may not be as pronounced as perceived; advancements in data generation technologies, precision agriculture sensing, and analysis and development approaches may need to await the expected revolutions. The applicability of CRISPR-Cas in crops for agriculture and food security is extensively reviewed, covering the nuances and important aspects currently shaping the technology.

Plant breeding has always required precision to define the trait in the plant genome. The present CRISPR-Cas editing tools, pioneered in bacteria as a microbial defense mechanism, have led to a fresh phase of genome editing in several organisms, including plants. New genome editing tools have emerged that widen the choice available for a defined application, each having unique features such as precision and off-target level. Any genome editing work actually begins with the identification of the target site in the appropriate sequence. Other innovations such as high-throughput sequencing and sequencing-by-synthesis (SBS) also aid gRNA design and access to genebanks of target sequences across organisms [78, 79, 75].

Precision breeding strategies

Genome editing offers a wide spectrum of precision breeding opportunities. It allows gene-function analyses and the insertion of valuable traits into breeding programs much more efficiently than classical methods. These approaches are certainly faster and less cumbersome than, for example, 8D or 12D backcrossing, as both marker-assisted selection (MAS) and genome-wide association studies (GWAS) using traditional SNPs or DArT markers require expensive resources in many mapping and breeding programs; it is, therefore, not surprising that many scientists in the field of molecular data have already started using these state-of-the-art technologies. Precision breeding using genome editing can also be considered as an end-to-end rapid MAS that identifies gene knockouts in the first or second generation, followed by pollen guard and simple checks for the presence of the target allele(s). Editing advances also allow functional redundancy in families that are difficult to breed together; layering multiple single precision-edited QTLs, genes, or gene combinations allows breeders to capture more of the natural diversity through very high numbers of progenitors and family sizes. Furthermore, genome-editing techniques have been used to assist complex traits such as those with protoxenia or phytonutrient layering at specific times.

Genome editing also has the potential to transform the entire approach to integration of phenomics and breeding programs. Natural diversity is used to assemble the best options in an optimal combination, in an optimal input situation and, eventually, to produce the best risk-protected product. This is then multiplication, with some sensitivity tests being done for more complex natural molecules where any increase in non-target risk from disease or environmental factors warrants consideration for a synthetic version of the natural molecule. Accelerated breeding for precision within proven integrated production systems (IPPS) can be a reality. It hinges on the quality of the phenomics and how that quality continues to evolve within the breeding process. The roll-out of advanced field sensors, for example, will provide constant improvement in the classification of canopy health, canopy development, crop yield, and product quality [80, 81, 82, 83].

Ethical and regulatory considerations

Public concern over GM technology remains apparent but is accompanied by a growing awareness of its role in global food security. Therefore, communication must bridge the values that influence opinions and the science that underpins technology. Further, risks are perceived asymmetrically; in a risk–benefit analysis of GM food, potential benefits for society or the environment are less important than avoided risks to health and the environment. Hence, authorities must ensure that commercial crops carry out the expected risk assessments, particularly in the global South, where some countries still lack a biosafety framework and GM crops have been forcibly imported despite voters' explicit rejection. Creating a transparent legal framework fosters trust and enables corresponding communication by public authorities and stakeholders. When such a framework is lacking, public authorities must apply the precautionary principle.

Nevertheless, public acceptance remains crucial for GM crop development, and stakeholders must demonstrate that their interests and concerns are taken seriously. The rapid proliferation of CRISPR-Cas also raises questions over the process and products, since modifying or deleting native genes may appear less unconventional. Others argue that these changes fundamentally alter a crop and should therefore follow existing regulatory procedures to ensure that monitoring after sale is possible. It is vital that stakeholders—including scientists—address ethical challenges associated with GM crops and genome-edited crops transparently and responsibly [84, 85, 86, 87].

Case studies in genome-edited crops

Genome editing technologies have enabled the precise engineering of genetic material to develop favourable traits in crops. The probabilities of utilising genome editing applications in the field have recently risen due to the efficient generation of many novel crop varieties; however, the inability to generate crops with natural non-GM traits still poses a problem. Several genome-edited crops have been developed and deployed commercially, and more are expected to reach markets soon.

Genome-edited products have already entered the market, either on a commercial basis or through experimental trials; a limited number of genome-edited plants have been authorised for market release, but safety evaluations specified by regulatory authorities have been limited in scope due to the absence of transformation-inherited components in edited organisms. Examples include non-GM off-type products with distinct high-value traits that are either currently marketed or expected to be available in the near future. Crops with enhanced metabolism, improved flowering cycles, or modified architectures are also gaining attention for applied breeding purposes [88, 89, 90].

Chapter - 6

Plant Tissue Culture and Micropropagation

Plant tissue culture refers to a set of techniques that allow the aseptic cultivation of plant tissues or cells in artificial media. The methods are based on the natural ability of a plant cell or tissue to regenerate a complete plant under controlled conditions. Thus, the formation of a new plant from a single cell, an isolated tissue, or an organ is basically asexual propagation in vitro. Apart from embryo culture, which has been routinely practiced for many years, the technology of plant tissue culture has also been resent as an important tool for horticulturists, plant breeders, and cytogeneticists aiming for germplasm preservation. The production of disease-free plants, preparation of virus-free stocks for mass propagation, and the supply of disease-free plants to flower nurseries and to farmers growing chrysanthumums, orchids, and other plants that are highly susceptible to viruses, have generated a large demand for meristem culture in recent years.

Somatic embryogenesis is the process by which somatic cells are induced to undergo all developmental processes leading to the formation of embryos. Somatic embryos differ from zygotic embryos in their origin; they arise from somatic tissues and/or cells that are not involved in fertilization. Somatic embryogenesis can be defined as the embryological manipulation of cells, tissues and organs of somatic or non-reproductive origin, resulting in single cells or tissues undergoing a series of developmental events leading to the formation of embryos. The total process eventually gives rise to embryos, which can then develop into whole plants. An important aspect of somatic embryogenesis is that in contrast to zygotic embryogenesis, any cell of the plant can be induced to form an embryo. Plant tissue culture or in vitro embryogenesis, represents an intriguing feature of higher plants, since it implies a high cell plasticity and allows somatic cells to return to a profound embryonic state. Though polyembryony, in a strict sense, can be defined as the process of development of more than one embryo from a single fertilized ovule embedded within the same seed, it is commonly understood to encompass any instance of the development of more than one embryo from a single ovule whether fertilized or not [91, 92, 93, 94].

Fundamentals of plant tissue culture

In plant tissue culture, asexual processes are used to produce large numbers of new plants. It depends on techniques that create and maintain sterile conditions needed for the growth of cells and tissues outside their natural environment. The basic plant tissue culture techniques include the establishment of aseptic conditions for culture, the production of a suitable growth medium, and the specification of the proper microenvironment required for the growth of the cultured tissues or cells. Natural agar, which is an extract of seaweed, is routinely used as a gelling agent for the media. In general, a mass of cells, tissues, or organs obtained in vitro can be manipulated to undergo somatic embryogenesis. During the earlier stages of induction, micropropagation systems require considerable investment in growth rooms and equipment. However, once an efficient micropropagation system has been developed, production can be intensive and large-scale.

Micropropagation encompasses a set of techniques that emphasise the establishment of aseptic cultures of selected plant material followed by the initiation of multiple shoots or roots as an intermediate step. The initial step involves the establishment of axenic conditions for culture, followed by the formation of a suitable growth medium. This is followed by the specification of proper plant growth temperature, light intensity and photoperiod. The aseptically cultured explants can undergo multiple shoot formation as an intermediate step. Micropropagation of virus-diseased plants is another area of considerable interest. A variety of methods are employed for producing virus-free plants. The occurrence of certain plant viruses subeptively in apical meristems has provided a possible approach for the eradication of these viruses from infected plants. Such meristems when cultured on an appropriate medium can give rise to axenic plants. These plants are usually transferred to soil for propagation, and the progeny checked for the absence of virus [95, 96, 97, 98].

Somatic embryogenesis

Is a form of plant tissue culture through which adventitious embryos can be induced in vitro on the explants such as cotyledons, leaf bases, and hypocotyls. Several cells within the explants undergo dedifferentiation to form a callus and later on can be induced to form somatic embryos. It is observed that generally the embryos and its derivatives developed directly on the explants are better than that of the embryos developed from a secondary callus. Such embryos can be developed from immature, mature and even senescent tissues. Generally, somatic embryos are produced through two routes: direct or indirect pathways.

In the direct pathway, somatic embryos are developed directly from explants without the formation of a callus phase. The precursors of the embryos are formed either from the epidermis of the explant or from its underlying tissues. The inducing and developmental phases can occur on the same medium. In indirect embryogenesis, explants normally form a callus and somatic embryos are produced from this callus. Although in both cases the embryos arise from haploid somatic cells, the three-dimensional structure of the embryo is maintained. Somatic embryos are known to form on cotyledons of several crop plants and produce plants in various species. Somatic embryogenesis is important for the large scale clonal propagation of a number of important crops, regeneration of hybrids and production of transgenic plants [99, 91, 100].

Micropropagation techniques

Include the culturing of ex-plants in aseptic conditions on suitable growth media containing nutrients, hormones, and other growth enhancers, leading to the formation of multiple daughter shoots. The plantlets produced from the mother plant are disease-free and are transferred to pots or bags after hardening. Propagation can be scaled up using liquid culture and bioreactors.

The technique has been successfully applied to various agricultural, horticultural, and forestry crops. The micropropagation industry of ornamental and horticultural plants, banana, sugarcane, coconut, and forestry is well established in different parts of the world and contributes significantly to the economy. These techniques assist in providing large quantities of healthy planting material for horticultural, ornamental, medicinal, forestry, and agro-forestry species. Commercial production and marketing of quality disease-free propagation material in sufficient quantities have enormous economic potential.

Plant-microbe interactions in the rhizosphere influence plant growth and nutrient availability through various mechanisms. Early stages of the root–microbe interaction can be utilized for developing inoculants that act directly in the rhizosphere zone or laterally to increase the bioavailability of nutrients. Such zone-level interactions provide better opportunities for the biological management of confined soil-borne diseases and for developing area-specific biofertilizers. Assessment of soil enzyme activities is a useful tool for determining soil fertility and evaluating soil health [101, 102, 103].

Virus-free plant production

Meristem culture of plants known to be infected by viruses can be performed to eliminate the pathogen. Detection and characterization of plant virus infections using virus-specific nucleic acid probes have provided a solid foundation for the virus sanitation of important crop plants. Various crop plants can be produced free from different viruses using meristem or shoot-tip culture techniques. Apart from meristem culture, it is also feasible to eliminate systemic or non-systemic virus infections by selecting plant variants resistant to those viruses or using other techniques of plant biotechnology. The availability of virus-free planting material in vegetable crops is one of the major requirements for vegetable planting in areas infested with virus diseases.

Leek, potato, garlic, onion, carrot, celery, cucumber, tomato, pepper, grape, strawberry, and berry-producing plants are produced virus-free by meristem culture. Raspberry, currant, and strawberry plants can be produced free from all known virus infections by meristem culture and by tissue culture of explants in an appropriate growth medium. Virus-specific PCR, RT-PCR, or immune hybridization techniques can be employed to evaluate the sanitary status of the plant material. All these plant species can safely be multiplied virus-free in large numbers on sterilized media in vitro or ex-plant culture technique and transferred to the greenhouse or hardening chamber. The hardening of explants and sterilization of the growth medium with antimycotic substances instead of antibiotics enables these explants to be put directly in the soil without further treatment. Such virus-free plants start fruiting earlier and yield healthy fruits with good marketable quality. Virus-free plants in horticultural crops also help in the post-harvest trade of crops without any fear of transmitting the virus diseases to other healthy plants [104, 105, 106].

Commercial applications

of these techniques include production of disease-free tissue-cultured plants, rapid propagation of true-to-type disease-free planting material for horticultural crops, the emergence of genetically modified crops, improvement of post-harvest quality of fruits and vegetables, and development of biopesticides. The annual global economic impact of transgenic crops grown over the last two decades has been estimated at US$186 billion. In India, benefit-cost analyses reveal very high Payback returns for certain GM crops (for example, insect-resistant cotton), leading to the conclusion that India should continue with active research in all biotechnological areas related to modern agriculture [107, 108, 109, 107, 108, 109].

Chapter - 7

Biological Control and Biopesticides

Biological control harnesses microbial, predator, or parasite inoculation to enhance natural pest regulation. Its ecological underpinnings enable compatibility with integrated pest management (IPM) and minimize adverse effects. Microbial agents—fungal, bacterial, and viral—offer an extensive, metabolically diverse resource pool. Insect predators and parasitoids support pest suppression. Biopesticides, derived from living origins, evolve through discovery, formulation, and toxicological testing for approval.

Combinations of biological strategies with other controls in cautionary sequences augment effectiveness while guarding against selection pressure. With minimal non-target risks, biological methods assist environmental protection, facilitating web health, water cleanliness, and biodiversity. Yet, successful deployment is not guaranteed and requires proper sequencing.

Biological pest management draws upon the ecosystem's inherent defenses against insect pests. While general ecological principles underpin this science, microbial biocontrol agents and insect natural enemies are major resources. Biopesticides and other biocontrol agents are biologically-based means for insect pest suppression, functioning through active substances produced from living organisms.

Biological control is profoundly eco-centric and embodies the concept that the natural environment should be exploited to its fullest extent when seeking control measures. For this reason, such control strategies—though embracing a much broader array of components—are inherently complementary to those of integrated pest management (IPM) and of greater ambient compatibility. Nevertheless, the very fact that biological control relies on the natural ability of the environment to suppress pest populations also implies that the implementation of such control measures does not guarantee success, requiring careful consideration of the ecological conditions necessary for such control to operate.

Principles of biological pest control

Biological pest control is based on the natural regulatory mechanisms that limit the growth and build-up of pest populations. It uses live organisms to reduce pest populations and crop damage or provide secondary benefits on a small scale. Biological control can also be facilitated through the introduction of reduced-risk, selective insecticides that improve natural control. Ecological interpretation of crop population dynamics should pay close attention to natural pest regulation and describe how particular species interactions can be used to improve pest management systems and reduce chemical pesticide inputs.

Biological pest control exploits the interaction of living organisms in ecosystems for pest management and is a major component of IPM programs worldwide. Studies of pest population dynamics, particularly model-based studies, offer direction for biological control. These studies conclude that pest populations are usually regulated by natural enemies and emphasize the diversity of these enemies. At the practical level, pest control using biological control agents with high apparent effectiveness in specific crops in specific areas is a critical part of the continued success of IPM programs worldwide [110, 111, 112].

Microbial biocontrol agents

Fungal, bacterial, and viral biocontrol agents constitute the main groups of microorganisms used in biological control of pests and pathogens. Major fungal agents include the genus Beauveria (Entomopathogenic fungi), Metarhizium (Entomopathogenic fungi), Trichoderma (Parasitoids), Fusarium spp. (Myco-insecticides), Pochonia chlamydosporia (Nematophagous fungi), Lecanicillium spp. (Entomopathogenic fungi), and Coniothyrium spp. (Myco-insecticides). The main mechanisms through which these fungal agents confer pest control are the secretion of toxic metabolites (such as antibiotics, secondary metabolites, and mycotoxins), mycoparasitism, and nematophagus behavior. The most prominent bacterial agents are

Bacillus thuringiensis (producing insecticidal crystal proteins acting on the midgut epithelium of certain insect larvae), Bacillus subtilis (plates on plant leaf surfaces), and Pseudomonas (producing antifungal compounds). Other genera such as Lysinibacillus, Burkholderia, and certain Gram-negative genera are also important biocontrol agents. Mycoviruses are also being explored as biological control agents.

Biopesticides are biological control agents based on living organisms or their toxic products that are used to prevent, control, or destroy harmful organisms. The idea of utilizing natural enemies of agricultural pests dates back to ancient times. However, industrial production of biopesticides using encapsulation or formulation technologies and their commercial application in agroecosystems emerged around the 1990s. Biopesticides mainly include fungal, bacterial, viral, and plant products used for pest regulation in crops and vegetables. Presently, a large number of biopesticide formulations are being developed and utilized worldwide for various pests and diseases by either using the organism per se or through the active principal of the organism [113, 114, 115].

Biopesticide development

Once potential biocontrol agents have been identified, a population must be screened for biocontrol efficacy and a strain selected for development as a commercial product. The steps involved in formulating a product that meets the regulatory standards have been described. Initial field trials may employ/compare unformulated sponge cakes or crude formulations, but regulations eventually require a finely formulated bio-agent. These products contain living organisms or their metabolites, and current definitions of biopesticides require that all biocontrol agents must be tested, even though chemical pesticides have long been registered on the basis of a formulated product without any requirements for formulation.

The major classes of biopesticide include a living organism, a metabolite of a living organism, or a dead or inactive organism. For example, chitinase is produced by bacteria or fungi for biocontrol of fungal diseases in plants. An effective biocontrol product must be able to control the target disease in the location and on the crop for which it is intended when applied under the environmental conditions expected during use. It must also have a high degree of competitiveness for the biological niche and must have rapid kill action [116, 117, 115].

Integration with IPM programs

Integration of biological control measures with other pest and disease management strategies is essential for sustainable crop production. In the case of pests, biological control measures require integration into decision support systems that guide producers when to release the agents for greatest impact. Effective timing also ensures that the biological control agents are compatible with other components of the integrated pest management program. Similarly, biological control of soil-borne diseases works best when included in an integrated disease management program that incorporates the best features of multiple management practices aimed at soil improvement and disease suppression.

Biological control could include use of microbial, viral, or nematode products or vaccines for management of an insect or the causal agent of a disease. In these systems, timing of the application needs to coincide with the life cycle of the target pest or pathogen for success to be achieved. In some instances, the biological control measure is used as a preparatory or preventative step. Thus, pathogenic fungi can be utilized to establish control of sclerotia or oospores in the soil before the deployment of the main crop. For long-lived crops, biological control can also be used at the end of the cropping cycle to target disposal of the residues by soil saprophytes. Integrated pest management applications of biological control offer a useful route for enhancing support for the continued development of these technologies [51, 118, 119].

Environmental safety of biocontrol

Biological pest control has a strong ecological base as it exploits nature's own mechanisms to maintain a healthy balance in pest populations. The understanding of these naturally occurring predator-prey relationships in the ecosystem has permitted the identification of useful microorganisms capable of pest control. Furthermore, with the present-day emphasis on sustainable development, biological control has gained much-needed interest as an environmentally safe and ecologically compatible alternative to chemical insecticides. Unlike chemicals, which indiscriminately kill all insects in the treated area, the population of beneficial insects, including predators and parasitoids, is not affected by a successful biocontrol program. Ectoparasites of foliage-dwelling pests are also kept under check by local sources of parasitoids and predators. There is plenty of information available on the biological control of specific insect pests through the use of predators, parasites, pathogens, and competitors. Research in this area, therefore, primarily deals with the isolation, identification, characterization, testing for efficacy, appropriate formulation, storage, and costing of microbial biocontrol agents.

Integration of microbial biocontrol agents with other pest control measures of an integrated pest management (IPM) program, particularly the cultural and chemical methods, enhances the compatibility and effectiveness of these alternatives. There is considerable evidence to show that the use of microbial biocontrol agents does not kill off beneficial and innocuous insects. Therefore, their inclusion at strategic intervals in an IPM program can allow the pest population to build up to levels that can be effectively controlled with these agents. The impact of biocontrol on natural ecosystems has been less explored. Although most biological control agents are native to the area of application, leapfrogging of biocontrol agents over natural geographical barriers could lead to a dichotomy in the natural landscape on either side of the introduced barrier. Risk and impact assessments of these control agents can reduce the likelihood of such unwanted effects [120, 121, 122].

Chapter - 8

Soil Biotechnology and Soil Health

Soil health directly influences crop yield and health. The disturbance of soil structure, imbalanced nutrient applications, and chemical fertilizers directs to loss of soil fertility and biodiversity. Soil organic carbon content, basic nutrient status, and soil microbiome diversity support plant health under stressful environments. Soil microbiome diversity has significant direct and indirect roles in nutrient cycling and helps the plants in healthy growing conditions. Biofertilizers and soil amendments facilitate biological health that prompts crop production. The application of PGPR and biofertilizers enhances microbial diversity in soil. Increasing diversity in the rhizosphere community will improve soil quality as well as overall crop health. Plant health is also modulated through the regulation of soil enzyme activities. Soil enzymes are biocatalysts that control the rate of metabolism and enzyme activity can indicate soil function and health. To produce high-quality agricultural products, soil resources should be well managed. Important sustainable soil management practices such as balanced fertilization, organic manure application, no-tillage, enhancing soil respiration, and reducing erosion should be adopted.

Soil is a living environment with a variety of communities of living organisms especially microorganisms. The healthy microbiome contributes directly to the growth and development of plants, enabling them to tolerate biotic and abiotic stress. All plants maintain a diverse variety of microorganisms, creating a unique microhabitat termed as ‘rhizosphere’ that is conducive for plant growth. Proper management of both soil and rhizosphere health is crucial for healthy crop production. The application of appropriate biofertilizers and organic manures in soil will improve soil and crop health. Plant health management requirements like soil fertility, microbial community structure, enzyme activity, and mineral composition should be addressed to ensure the continuous growth of healthy crops [123, 124, 125].

Soil microbiome and plant growth

Soil microbiome diversity strongly determines N and P biogeochemical cycling, and is vital for controlling plant growth and health. Rhizobium biofertilizer significantly and holistically stimulated plant growth of chickpea, soybean, and other legumes, enhancing N nutrition and bioactive metabolites. Microbial biofertilizers like Azospirillum, Azotobacter, and P-solubilizing bacteria are well-recognized for their effects on plant growth; their application in crops leads to increased plant diversity and productivity. Multiple biofertilizer combinations have resulted in enhanced crop performance. Microbial diversity in the rhizosphere is promoted by the application of beneficial bacteria, which modulate microbial community structure and activate functional genes. N2-fixing Bradyrhizobium can strongly enhance P cycling in the rhizosphere of soybeans grown in P-deficient soils. Importantly species diversity of the rhizobiome of soybean roots correlates positively with plant growth parameters and N2-fixation efficiency, thus could be targeted for improving rhizobiome productivity.

Soil microbial diversity and biofertilizers can contribute sustainably as plant growth-promoters (PGPs), reducing chemical fertilizers. N2-fixing Rhizobium spp. symbiotically associated with legumes are extensively utilized as strains and commercial biofertilizers worldwide. Knowledge of plant–microbe, such as the interactions between legumes and rhizobia understates the playing role of microbes in plant growth promotion; the direct contributions of N2-fixing Rhizobium in soil ecology would be ignored. NR-based N2 fixation of N availability for plant growth introduces feedbacks to P biogeochemical cycling in the rhizosphere during plant growth conducting significant advantages. Microbial biofertilizers derived from N2-fixing bacterium can and significantly stimulate the growth of Chickpea in terms of shoot height, number of branches and flowers, dry weight, N2–fixation and bioactive metabolites; their application induced alterations in soil microbial community structure, and triggered microbial functional responses serving as N2–fixation bioresources [126, 127, 128].

Biofertilizers and soil amendments

The application of biofertilizers and soil amendments serves as a key approach among soil biotechnology practices that improve soil fertility and plant growth. The inoculation of plant growth-promoting rhizobacteria (PGPR) as biofertilizers enhances the availability of nutrients and induces systemic resistance in host plants while conferring additional beneficial effects on non-host plants. The installation of single or dual cultures of PGPR strains in the rhizosphere, along with dry cell powder, cow dung, or vermicompost, improves the growth of both chickpea and radish and also imparts some residual effects on the growth of sunflower.

Increasing land degradation and the increasing cost of chemical fertilizers have pushed soil health to a critical stage. The introduction of biofertilizers, which exploit the microscopic flora of soils, is considered an important component in both development and research of agriculture. Bioinoculation with PGPR, AM fungi, or N-fixing or P-solubilizing bacteria can enhance plant growth and yield not only by supplying nutrients directly through biological processes (e.g., N2 fixation or solubilization) but also by enhancing nutrient availability and uptake through a wide range of other mechanisms [129, 130, 131].

Rhizosphere biotechnology

The rhizosphere zone is the most dynamic component of a soil. When roots exude organic substances such as carbohydrate, protein, and organic acid, the soil located close to the root of a plant becomes a very active zone for chemical, microbial, and biological activity. The microbes rapidly surround the roots, and the activities of the organisms in this narrow volume have a profound influence on the overall character of the soil environment. These rhizosphere organisms interact with the plants both positively and negatively. The interaction of pathogens can create diseases. On the other hand, some beneficial microbes help in plant growth and development. Beneficial fungi and bacteria increase nutrient availability for the plants and improve plant health. They promote seed germination, diversification, root development and enhance plant growth and productivity. The application of plant growth-promoting rhizobacteria like Azospirillum, Azotobacter, Bacillus, Pseudomonas, and Mycorrhizal Sp. individually or by combination in the rhizosphere actively plays an important role in plant development.

The natural flora around the plant roots and methods to manipulate the composition of the rhizosphere have been effectively used to promote growth. Organic amendments like FYM, vermicompost, and green leaf manure released nutrients that stimulated growth, yield, and nutrient composition of plants. In addition, pre-application of NPK and animal manure at appropriate rates increases the growth and nutrient availability in the rhizosphere zone. Enhanced activity of soil enzymes like dehydrogenase, urease, phosphatase, and alkaline phosphatase in the rhizosphere shows improvement in soil health and fertility. Thus, it is clear that the management of rhizosphere organisms with different carriers is needed for eco-friendly production of quality produce [132, 133, 134].

Soil enzyme activities

Play a crucial role in maintaining soil health and function. The overall activity of soil enzymes or activity of a particular enzyme can be used as an indicator of the processes taking place in a particular soil under a specific land use and availability of nutrients. Enzyme levels in the soil can provide information on nutrient cycling. The soil enzyme activity in healthy soil is always at an optimum level. Administration of appropriate quantity of fertilizers improves the activity of several soil enzymes within permissible limits.

Management through crop rotation with legumes, use of green manuring, application of organic manures and fertilizers, limiting of tillage, substitution of minimum tillage by conservation tillage, soil mulching, seeding in ridges, incorporation of crop residue, sub-soiling and addition of plant cover during winter improve the soil quality with respect to enzyme activity. Certain land management practices negatively affect the biological quality and soil enzyme activity [135, 136, 137].

Sustainable soil management

Soil performs various functions and is vital for food production, ecosystem services, and a stable environment. Ensures the continued provision of these services while maintaining soil fertility and agricultural yields in the long term. It aims to secure a continuous supply of ecosystem services, including the provision of biomass, mitigation of climate change, maintenance of biodiversity, purification of surface and groundwater, and natural hazard regulation. Soil management practices and the choices made can favor or adversely affect the delivery of these services, especially over the long term.

Soil quality depends on the inherent properties of soils, local climate, ecosystem, land use, and management practices and should be considered from a holistic points view. Agricultural practices that maintain the natural resource base while sustainably utilizing it are defined here as sustainable soil management. These include measures that integrate physical, chemical, and biological properties at the landscape scale and the management of soils with nature's capability and functioning. Sustainable soil management considers the specific interactions between environmental, economic. and ,social aspects, and as such, it is not always synonymous with the concept of sustainability, in economic terms. Soil plays a vital role in maintaining the natural resource base, capturing and storing carbon, providing a physical medium for the growth of crops and trees, providing mineral nutrients for biomass production, regulating the water cycle, filtering surface and groundwater, and supporting biodiversity. Soil management practices and decisions can enhance or compromise the provision of these services.

Sustainable soil management takes into account not only the inherent properties of soils and the local climate and ecosystem but also considers factors related to land use and the adoption of improved technologies. Cement talk! Data show that the status of soils in many areas of the world has deteriorated as a consequence of human activity, while in other areas it has improved. The latter situation, when soil quality has been maintained, restored, or improved, is commonly referred to as sustainable soil management, although, by definition, sustainability is a much broader concept. It should thus be recognized that sustainable soil management does not necessarily lead to sustainability per se. The integration of physical, chemical, and biological properties of soils at appropriate spatial scales and the management of soils in harmony with nature's capability ensure improved productivity and quality of land. Such management supports the process of maintaining the natural resource base and provides the environment, together with the ecosystem, with the capacity to regulate climate, filter surface and groundwater, and support biodiversity [138, 139, 140, 138, 139, 140].

Chapter - 9

Plant Nutrition and Biofertilizer Technologies

Essential plant nutrients—the macronutrients nitrogen, phosphorus, sulfur, calcium, and magnesium; the micronutrients iron, manganese, zinc, boron, copper, molybdenum, and chlorine—are the fundamental building blocks of metabolic processes and serve critical roles in plant development and quality. Sufficient supply of these elements is vital for increasing crop yields and sustaining food and by-product quality. Biofertilizers—mainly microbial preparations—support crop growth, thereby enhancing the quantity and quality of food, fodder, fuel, and raw materials. They act both through direct contribution of nutrients essential for plant growth (e.g., nitrogen fixed by diazotrophs or phosphorus solubilized by phosphate-solubilizing microbes) and by improving nutrient bioavailability and physiological functioning of the host plant (e.g., PGPB species and arbuscular mycorrhizal fungi). Use of biofertilizers in agriculture has gained momentum through rising input costs, increased awareness of environmental hazards caused by chemical fertilizers, the sustained need for increased productivity, and the clear role of related microorganisms in the biogeochemical cycles of nutrients.

Biotechnology, which provides tools to overcome natural limitations, enables enhancement of nodulation and repair of dysfunctional symbiosis, creation of phosphatesolubilizing endophytes, and development of plant genotypes suitable for specific soil or climatic conditions and/or capable of supporting superior N-fixing associations themselves, represents an important area in this context. The contribution of N2-fixing, P-solubilizing, K-solubilizing, and other biofertilizer microbes to plant growth and quality has been broadly reviewed elsewhere. Increasing levels of essential nutrients and other quality-enhancing constituents (flavor compounds, vitamins, minerals, etc.) through the use of biofertilizers provide better health at lesser cost, contributing to a sustainable food supply with assured health for livestock and humans.

Essential plant nutrients

Most minerals required by plants originate from earth's crust. The concept of essential nutrients is based on three criteria: (1) required for normal growth and development; (2) required for at least one specific metabolic function; (3) cause consistently abnormal growth and development when absent. The essential nutrients are categorized into primary, secondary, and micronutrients according to the relative quantity made available.

Macronutrients required in large quantities are nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. Micronutrients needed in small amounts are iron, manganese, cobalt, zinc, copper, molybdenum, and boron. Their relative abundance in plants is: C > O > H > N > Ca > K > Mg > S > P > Fe > Cl > Zn > Mn > B > Cu > Mo. Nitrogen, potassium, silicon, calcium, magnesium, iron, manganese, and copper are regarded as nutrients that have a significant effect on fruit quality [141, 142, 143].

Microbial biofertilizers

Biofertilizer is a substance that contains living microorganisms, which, when applied to seed, plant surface, or soil, colonizes the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant. Following the International Organization for Standardization, biofertilizers are products containing microorganisms that promote sustainable agriculture by increasing crop yield or enhancing soil fertility, whereas a biofertilizer is a product containing genetically manipulated microorganisms, usually bacteria, fungi, or algae, that can supply nutrients for plants.

The major groups of microorganisms that can be used as biological fertilizers include nitrogen-fixing bacteria (e.g., Azotobacter, Azospirillium, Rhizobium, and Frankia), phosphate-solubilizing bacteria (e.g., mycorrhizal fungi and Pseudomonas), potassium-solubilizing bacteria (e.g., Bacillus and Pseudomonas), plant growth-promoting rhizobacteria (PGPR), and phosphate-solubilizing and nitrogen-fixing cyanobacteria and blue-green algae (e.g., Nostoc and Anabaena). These microorganisms are capable of mobilizing nutrients and enhancing fertility in the soil to help improve plant vigor and productivity. Application of plant growth-promoting rhizobacteria (PGPR) inoculated into vegetable seeds improved plant growth, yield, and quality. Such bio-inoculants enhance seedling metal uptake and resistance to metal stress among crops grown on contaminated soil. The biotechnology of these plant–microbial interactions provided practical approaches for enhancing the nitrogen economy of cereal crops and resulted in increased crop yields and soil fertility [144, 145, 128].

Nitrogen fixation biotechnology

Biotechnology offers several approaches to enhance nitrogen fixation in crops, which is of particular significance given the essential role of nitrogen in plant growth. Application of N-fixing microorganisms as biofertilizers to promote dependable and cost-effective nitrogen supply for crops is one of the prominent areas of ongoing research. Based on current developments, a synopsis of nitrogen fixation biotechnology has been presented, focusing on various aspects such as progress in the introduction of plant growth-promoting rhizobacteria, the utilization of nitrogen-fixing actinobacteria in association with plants, the application of eukaryotic algae and other eukaryotic nitrogen fixers as biofertilizers and subterranean symbiotic N-fixing cyanobacteria and the application of genetically engineered microorganisms for enhanced N-fixation.

Plant Nitrogen Needs and Biological N-Fixation

Nitrogen is a key nutrient that has a major influence on plant growth and production, affecting growth vigor, yield quantity and quality, and economic returns. Nitrogen content is often recognized as a limiting factor contributing to lower soil fertility and crop production. For sustainable agricultural practices, it is essential to maintain soil health and fertility. Biological N-fixation is a natural process through which atmospheric N2 is reduced to ammonia by certain microorganisms, called N-fixing bacteria. The mechanism of fixation of N2 is complex and time-consuming, demanding high external energy, metabolic intermediates, and special enzymes (nitrogenase) cofactor. Therefore, nitrogen-fixing organisms have been under study for a very long time, and attempts are in progress to apply these organisms as biofertilizers to crop plants for effective N-supply [146, 147, 148].

Phosphate solubilizing microbes

Microbial biofertilizers have gained considerable attention from researchers, industries, and society. Phosphate-solubilizing microorganisms (PSMs) have been found to augment plant growth and development through various mechanisms, including improved soil physicochemical properties, enhancement of rhizosphere conditions, and increased nutrient uptake. Among the soil nutrients, phosphorus is relatively less mobile and thus unavailable to a major portion of soil microbial populations and higher plants. The first major limiting macro-nutrient for crop production is the availability of phosphorus in the soil. Apart from N, phosphorus is also one of the nutrients desired in large quantities by the plant. Phosphorus is indispensable for crop growth and development due to its roles in energy transfer, photosynthesis, nutrient movement within plants, and nucleic acid synthesis. In addition to being an essential nutrient, phosphorus is also one of the fundamental components of the phospholipids that supply energy for the metabolic activities of the living cells. Biofertilizers based on phosphate-solubilizing microorganisms play an important role in supplying phosphorus to a wide variety of crops.

From the perspective of protection and promotion of an environment-friendly sustainable agriculture, the role of phosphate-solubilizing microorganisms in cropping practices has become a matter of close interest. Recent research has brought new information on the nutritional complexities that can develop under practical cropping conditions. PSMs produce organic acids, enzymes, exudates, and plant-growth substrates, which enhance the availability of phosphorus to plants. Phosphate-solubilizing microorganisms can be obtained from various natural sources such as forest land, grassland, grazing land, rice field, and leguminous plants [149, 150, 151].

Impact on crop quality

Crop quality dimensions like taste, nutritional value, shelf life, and processing and cooking characteristics determine how food is consumed and marketed. Nutrition and marketability are particularly important for fruits and vegetables; higher levels of vitamins, carotenoids, and phytonutrients improve health values. Yet producing high-quality crops is difficult, exemplified by high rejection rates for apples and potatoes due to poor appearance. Economic constraints drive marketing distances, increasing post-harvest losses caused by pathogens, physiological disorders, rough handling, and transportation. Biotechnology helps address these challenges by preserving nutrient content during storage, reducing microbial growth, and detecting deterioration.

Food quality encompasses sensory properties (appearance, texture, flavor, aroma) and nutrient content, impacting consumer choices. Acceptable flavor, taste, and aroma require complex mixtures of volatile, non-volatile, and soluble compounds synthesized during growth and ripening. Biochemical processes influence color, texture, and flavor and can be altered to enhance or diminish specific traits. Long shelf life and ease of handling and transportation also play major roles. Healthy food rich in vitamins, minerals, exercise-promoting substances, and taste-appeal volatiles attracts more consumers [152, 153, 154].

Chapter - 10

Post-Harvest Biotechnology and Food Quality

Postharvest losses pose a major impediment to global food security. Annually, around 74 billion USD of fruit, vegetables, and tuber yields—value items for nutritionally imbalanced diets—are wasted. Despite technological advances, worldwide losses remain high. Microbial-based biosolutions can reduce perishability and add value. Enzymatic formulations support fruit and vegetable storage. Precise fruit-climacteric models optimize ripening and reduce decay. Sensor networks track crop quality during transport and storage, while rapid assays monitor food-pathogen interactions. Biotechnological tools also address epidemic-breaking pathogen testing, multiresistant Pseudomonas spp. detection, and dry green mango disease diagnosis.

Maintaining dietary nutritional potency is a major challenge. Well-designed postharvest technologies conserve antioxidants, vitamins, and help develop fortified edible films. Functions that preserve freshness while also preventing spoilage are vital for consumer satisfaction. Taste, texture, and market price are some quality determinants for fresh and processed products [155, 156, 157].

Post-harvest losses and challenges

Food loss and waste is a global challenge with major economic and environmental effects: around 1 billion tonnes of food are wasted each year, costing about $700 billion annually, while food loss accounts for more than 25% of the world's agricultural footprint. Advanced and innovative solutions are essential to prevent economic losses, preserve nutrients and organoleptic properties, fight post-harvest pathogens, and develop rapid quality-control methods along the food-supply chain. Some areas of concern include: (1) control of post-harvest pathogens; (2) food-safety and quality-assessment methods; (3) extension of food shelf-life; and (4) DNA biosensors.

Grain and vegetable products are subject to microbial spoilage, which causes huge economic losses. Pathogens that can cause spoilage include genera such as Aspergillus, Penicillium, Botrytis, Alternaria, Colletotrichum, Xanthomonas, Pseudomonas and Listeria. Identification techniques for foodborne pathogens continue to move toward the implementation of biosensors, which enable easy on-site detection and quantification. Many studies have addressed the use of ELISA, PCR, LAMP and/or biosensors. Rapid detection methods are essential for the food industry and regulatory authorities because they shorten the detection time while maintaining high sensitivity and selectivity. Emerging diagnostic methods also include hyperspectral, electronic-nose and electronic-eye technologies capable of detecting chemical changes. In addition, there is a growing interest in odor and taste sensors based on immobilized microbes or olfactory-receptor proteins that provide a specific taste or smell profile of a food sample and in digital-imaging techniques for assessing food characteristics [158, 159, 160].

Biotechnology for shelf-life extension

Sustainable food production is insufficient without efforts to minimize post-harvest losses suffered by plant produce, especially fruits and vegetables. Post-harvest biotechnology offers innovative techniques for extending the shelf life of these products, including modified atmosphere storage, natural protective coatings, and biological control of post-harvest pathogens. Quality assessment technologies involving sensors, hyperspectral imaging, and other sophisticated analytical instruments can help detect such spoilage. Nutritional quality preservation of food products fortified with micronutrients is also important, especially for vulnerable populations.

Roughly one-third of the total food produced in the world is lost or wasted each year. Food loses density at the extremes of the supply chain: primarily in quantity closer to the producer and in quality closer to the consumer. Fruits and vegetables are the most commonly wasted foods, partly due to intrinsic characteristics of perishability and high moisture content. Such losses have become a pressing concern for the food security of an ever-growing global population, since fresh produce serve as a primary source of vitamins, minerals, and other health-promoting components. Managing spoilage organisms effectively and extending the marketable life of these products are critical to safeguarding consumer health while enhancing food availability and reducing waste [161, 162, 163].

Control of post-harvest pathogens

Losses of agricultural produce after harvest are a major challenge in food security and food waste issues because of reduced quantity and quality of available food. Many approaches for the control of post-harvest pathogens—including application of chemicals, use of high temperatures, UV-C radiation, and biological control—have been reported. Different varieties of fruits, vegetables, and cereals are susceptible to different groups of pathogens. The pathogens infect the crops at their weakest point, resulting in rot and spoilage. Improved requirements in fruit post-harvest treatment for the control of pathogens are to avoid residue of chemicals, ensure food safety, and develop effective, residue-free pathogen control methods. Rapid methods for detection of post-harvest pathogens—including a polymerase-chain-reaction-based method and detection based on a miniaturized real-time polymerase-chain-reaction instrument—are under development. For oranges, the command compound sepicide can be used as a washing substance.

The application of biological control components reduces pathogenic damage in several fruits and vegetables. Recent trials in strawberries demonstrated the production of a commercial preparation based on the biocontrol agent Pyranobacterium that achieved a significant reduction of rot disease. Other naturally obtained components for controlling pathogens—such as lipopeptides, saponins, essential oils, strobilurins, and others—have also been studied and identified as having great potential. The development of practical treatments and formulations that focus on the latest scientific data is strongly recommended. Integrated pest management guidelines supplemented by biocontrol components are expected to contribute to improved post-harvest management of different fruit and vegetable products, reducing dependence on chemical treatments [164, 51, 165].

Quality assessment technologies

Rapid-food quality assessment technologies suitable for industrial use are emerging; sensors for various volatile quantities, imaging-based techniques for physical observation, and analytical measures for compositional screening facilitate broad daily applications. Meanwhile, maintaining nutritional quality, ensuring the retention of primary ingredients, and providing fortified food on the market continue to be central issues for food biotechnology.

With the increasing demand for fresh and healthy food, post-harvest biotechnological research is developing techniques for food preservation during the supply chain, aiming to reduce both microbiological risk and nutritional losses. Mold activity on perishable foods, however, remains a challenge, and although several methods already exist for microbial growth control, few are applicable for quality retention. The chemical treatment of food has been applied for a long time, with several positive results; yet, the chemical compounds used remain a cause for public concern. Detection and removal methods are therefore essential to enable normal consumer safety, and several options suitable for industrial application have been proposed. Current biotechnological approaches focus on detection systems adapted to industry use, affordable biosensors for small companies, and new technologies — in particular the application of nanotechnology in the post-harvest phase — to improve packages and provide protective functions [166, 167, 168].

Nutritional quality preservation

Food Security acknowledges the vital role of edible quality preservation in post-harvest loss prevention. Nutritional losses remain substantial during both long- and short-term storage, and existing measures and technologies must be augmented through ongoing research. Microbial pathogens persist in stored fruits and vegetables, with detection and reduction central to quality safety. Technological advances in quality control and the advent of biofortified products contribute to post-harvest food safety through effective monitoring and quality enhancement. Climatic and storage conditions impact crop nutritional quality, and biotechnologically assisted crops are of particular interest in relation to fortification over poorer micronutrient sources.

Post-harvest food losses severely hamper food security. Estimates suggest that nearly one-third of all food produced globally is lost after harvest or wasted, amounting to about 1.3 billion tons each year. Well-known pathogens like Botrytis cinerea and Pythium sp. remain a major concern for stored fruits and vegetables. The potential of novel sensors for quality assessment is tremendous, combining manual sensors with optical imaging techniques and sophisticated chemometric analysis. Food fortification is another important approach, as increasing the nutritional value of food aids in the prevention of life-threatening diseases [163, 169, 161, 162].

Chapter - 11

Food Safety and Molecular Detection Techniques

Foodborne illnesses are caused by a wide range of microbiological agents, including bacteria, viruses, protozoa, fungi, and algae. These illnesses result in severe morbidity and mortality globally. Microbial contamination can occur at any stage of food production, from pre-harvest to post-harvest and storage, and may arise from contaminated water, surfaces, or food handlers. Although a large number of pathogens can contaminate food, the majority of illnesses are attributed to a small number of agents, including Salmonella spp., Escherichia coli, and Campylobacter. These pathogens are transmitted through contaminated food and water, and exposure can lead to severe health problems. Most notably, Salmonella spp. are common in poultry, eggs, fish, and meat, and infections can lead to abdominal pain, diarrhea, fever, vomiting, and sometimes death. Additionally, Vibrio parahaemolyticus is a leading cause of gastroenteritis in Asia; outbreaks are common during summer months, particularly related to raw or steamed shellfish consumption.

Many tests for food pathogen detection rely on culture methods, which are costly and time-consuming. Novel pathogen detection techniques, which are generally faster, simpler, and lower in cost, are urgently needed. PCR-based assays for pathogen detection can be designed based on the sequencing of pathogen-specific sequence regions. qPCR-based pathogen detection systems have been developed, and detection systems based on LAMP have been used for multiple pathogens, including E. coli O157:H7, Salmonella, and Campylobacter species. For highly contagious pathogens, such as Salmonella, portable qPCR systems have been developed for quick field detection. These assays are based on locked nucleic acid (LNA)-modified primers to reduce non-specific amplifications and improve specificity. A flexible and rapid LAMP detection system for multiple pathogens in food has also been developed. Rapid tests are available for the simultaneous detection of six pathogens in food. Biosensors specifically designed for food safety analysis have also been reported [170, 48, 171, 172].

Foodborne pathogens and risks

A range of pathogenic bacteria, viruses, and protozoa are present in food products that cause diseases in humans when consumed. Massive transmissions of foodborne pathogens can occur during the production stage, and as a result, food safety standards should be applied to all products at different environmental levels. The most affected food products are meat, poultry, eggs, milk, fish, and other seafood, followed by vegetables, fruits, and nuts. Outbreaks of foodborne illnesses have also been traced to products such as fresh and fresh-cut fruits and vegetables, fruit juices, and nuts susceptible to contamination by pathogenic bacteria or viruses. Despite careful selection of the food item and proper preparation methods, the consumer is still at risk of ingesting a contaminated product. Several pathogenic bacteria can now be detected in food and environmental samples by polymerase chain reaction (PCR)-based methods aimed at specific sequences of DNA and RNA; these methods have excellent sensitivity and specificity according to the type of assay observation made.

The presence of microbial and non-microbial toxins or other undesirable agents in foodstuffs represents a global concern for both public health safety and the economy. Specified foodborne pathogens can pose a risk to health or safety when they are present in food products. These detectable microorganisms or their toxins may be highly infectious, virulent, or pathogenic for humans, indicated by illness or death in animals or humans caused by eating the food, or are rapidly emerging as a serious public health hazard as a consequence of increased control and traceability. Food businesses should proactively manage the risk of contamination and establish predictive controls or validation procedures that assess the efficiency of their product safety management [173, 174, 175].

PCR-based food safety testing

Molecular techniques based on polymerase chain reaction (PCR) have been adapted to detect and identify foodborne pathogens in multiple food matrices, including various food types, such as meat, poultry, seafood, milk, and fresh produce, in environmental samples such as water, soil, and canning waste, and in clinical samples and food handlers. PCR assays can be designed for the detection of specific pathogens or pathogen groups, for monitoring virulence genes, and for subtyping isolates using amplification of repetitive regions. Multiplex PCR assays have also been developed to detect more than one pathogen species or genus in a single amplification reaction. These PCR-based assays fall into three major categories of food safety testing technology: presence or absence detection, quantification, and virulence assessment.

Absolute quantification methods attempt to determine the amount of a target pathogen in a food sample, and this is usually achieved using a standard curve derived from synthesised or cloned PCR products. Construction of a standard curve for absolute quantification requires that the standard and the field samples undergo the same extraction and analysis procedures. More recently, quantitative PCR using fluorescent dyes or reporter probes has been developed to allow rapid quantification of pathogens without the need for a standard curve. Quantification of pathogens in food samples is often complicated by the presence of PCR inhibitors, and matrix effects can also cause the abundance of the quantitated pathogen to be underestimated; therefore, care should be taken when interpreting quantitative results [176, 171, 177, 178].

Biosensors in food analysis

Food safety has become a crucial public health challenge, and specialized monitoring is required to ensure that food products contain acceptable levels of spoilage microorganisms and other toxic substances. Biosensors are electrochemical or optical-based analytical methods that combine the sensitivity of bioreceptors with the selectivity of chemical sensors. Unlike conventional detection methods, biosensor devices can show a measurable response in a short time, provide quantitative results, and be used directly with complex food matrixes, avoiding tedious enrichment or purification procedures. To assess the food matrix, more sensitive and selective assays are being developed and combined with nanomaterials and nanotechnology-based platforms. In addition, lab-on-a-chip devices dedicate to food processing.

The application of biosensors is beneficial for food quality and safety evaluation, detecting foodborne pathogens and toxins, controlling fermentation processes, and monitoring meat quality and fish freshness. Important approaches are summarized and discussed, and a trend toward a new generation of biosensors is highlighted. Major limitations and perspectives for a wider application of biosensors in food technology are also discussed [179, 180, 181, 182].

Traceability and authentication

Are critical areas in food security, focusing on documenting supply chain movement and product identification to mitigate food fraud and ensure food safety. Investments in detection methods and data management foster consumer confidence and enable the introduction of novel food products. Traceability systems track products through the entire supply chain, providing essential data to ensure food quality, prevent fraud, and enhance safety. Basic requirements include product handling information, stakeholder identities, and tracking locations. Data management allows rapid, reliable remedial measures in case of safety breaches. Automatic systems employ sensors and cameras connected to artificial intelligence for smart decision-making. Biosensors facilitate high-speed, on-site screening, while bio-informatics supports the establishment of labelling and tracking systems.

Food fraud encompasses product misrepresentation through false information, incorrect labelling, legislative breaches, or spelling violations. It affects consumer safety, plant health, and trade relations, especially in organic products, leading to financial losses. Entrepreneurs need reliable detection methods to sustain market growth and avoid illicit sales. Traceability is crucial for novel products, as public confidence depends on assurance that functional claims are credible. The food industry increasingly incorporates traceability systems to verify food origin and handling methods. Information from farm to fork is essential [183, 184, 185].

Rapid diagnostic technologies

Recent years have witnessed the widespread emergence of many infectious diseases. The COVID-19 pandemic highlighted the importance of rapid diagnosis for controlling the spread of pathogens. For many assays, speed is often crucial, but capture of additional parameters such as specificity, sensitivity, platforming, widespread availability, operation without complex equipment, ease of use, and low cost are often equally critical. Food safety and disease control in plants and animals have similar considerations, whether relying on reverse-transcription polymerase chain reaction (RT-PCR), high-resolution melting analysis, loop-mediated isothermal amplification (LAMP), biosensors, or other techniques. Such rapid diagnostic technologies are crucial for the safety of food and other products and are also broadly applicable to environmental and ecological monitoring.

Detection of foodborne pathogens must be fast, sensitive, and yet cost effective. For example, the common and deadly foodborne pathogen Listeria monocytogenes requires a detection time of no more than 12–24 hours. A plex-PCR assay that can detect up to eight different foodborne pathogens has also been developed. Another critical group includes patoens that generate biotoxins in food. Detection does not rely on growth of the microbes because they are inactivated during food processing. Rather, detection of the relevant components (nucleic acids, proteins, or toxins) within food samples is essential. For many assays, speed is often crucial, but capture of additional parameters such as specificity, sensitivity, platforming, widespread availability, operation without complex equipment, ease of use, and low cost are often equally critical. applied to the control of foodborne pathogens, for example, span platforms that include RT-PCR, LAMP, biosensors, and immunological detection [171, 178, 158].

Chapter – 12

Environmental Biotechnology in Agriculture

Environmental biotechnology supports sustainable food security by reducing pollution from production and processing. Scientific advances enable biological remediation or mitigation of environmental contamination, including heavy-metal, pesticide, and hormone pollution, as well as polluted wastewater. Phytoremediation techniques using trees capable of heavy-metal uptake effectively remove contaminants from soil. Sustainable production methods limit reliance on chemical fertilizers and pesticides, further reducing pollution. Wastewater call for treatment or reuse to prevent spread of pollutants.

Bioremediation involves the use of natural organisms or their products to eliminate environmental contaminants, including heavy metals, pesticides, and organic toxins. Contaminated sites are important to clean up due to their long-term environmental and health effects. Phytoremediation uses plants to clean contaminated soils and aquifers. Plant strategies for heavy-metal uptake and tolerance have been developed for species such as Brassica, Phragmites, Salix, and Populus. However, metal accumulation in edible parts remains a concern.

Wastewater contains nutrients and can be reused for irrigation after proper treatment. Biological treatment methods, such as activated sludge, include microbial culture to decompose organic matter. Integration of multiple treatment methods has also been suggested. Sustainable agricultural practices control fertilizer and pesticide application, enhancing soil quality through crop rotation, cover crops, and organic amendments. Integrating biochar application with other practices further reduces environmental degradation. An environmental risk assessment framework based on pollution and ecology identifies the acceptable range of agrochemicals for sustainable crop production [186, 187, 188].

Bioremediation of contaminated soils

Can be carried out by two different approaches: biostimulation and bioaugmentation. The first includes addition of nutrients and bioactive compounds to a naturally occurring microbial population, while the second approach involves increasing the degrading capacities of microorganisms present in soils with little native degrading ability. Several case studies have shown the capacity to biodegrade hydrocarbons, phenols, and solvents in contaminated soils, comparing the effects of natural attenuation versus biostimulation and bioaugmentation. The results have demonstrated that bioremediation is feasible and efficient.

Bioremediation is used to clean up soils contaminated by hydrocarbons resulting from oil spills, leaks of underground storage tanks, or inadequate disposal of waste oils. Whenever a diesel or petrol spill occurs, microorganisms native to the soil colonize the contaminated zone, degrading the fuel. Biostimulation can enhance this natural degradation process by adding nitrogen and phosphorous to the nutrient-depleted zone. Nutrients can also be injected into the soil according to the capabilities of the native microbial community [189, 190, 191].

Phytoremediation technologies

Phytoremediation employs living plants to restore polluted or contaminated soils, sediments, or aquifers, harnessing their natural capabilities. This approach is cost-effective due to the abundance of plant biomass, which, unlike chemicals, poses no threat to health or the environment. Various plants can accumulative, tolerate, or remit pollutants, including heavy metals, metalloids, persistent pseudo-organic pollutants, and radionuclides. Phytoremediation is applied in remediation, remediation, and reclamation, and suitable areas for projects can be evaluated by land property, past waste discharge, the type of contaminants, and the degree of pollution. The future of phytoremediation relies on transgenic approaches that improve radicle exudation and overexpression of phytoremediation-related genes.

Phytoremediation is a process that uses plants to stabilize or remediate polluted or contaminated soils, sediments, or aquifers, exploiting the natural abilities of plants to act as ecological filters. Phytoremediation is cost-effective due to the enormous biomass produced by higher plants. The biomass produced has many beneficial attributes, which are not disfigured with chemical contaminants, making phytoremediation environmentally safe. Phytoremediation is based on the use of plants that can uptake, tolerate, and/or render harmless metals, metalloids, persistent pseudo-organic pollutants, and radionuclides. The term is applied not only to decontamination activities but also to reclamation and remediation of damaged lands. Area-specific suitability indices can be formulated based on land property, past waste deposition, category of contaminants, and degree of pollution for selecting areas for phytoremediation. The effectiveness of phytoremediation in mitigating pollution loads in different contaminated territories has been substantiated. The technologies and strategies that hold better promises for future phytoremediation research and field practice require careful consideration. The future of phytoremediation lies in the use of transgenic plants capable of exuding higher amounts of suitable radicle exudates or expressing a higher activity of preidentified genes associated with the process of phytoremediation in plants [192, 193, 194, 192, 193, 194].

Wastewater reuse and treatment

Techniques and safety considerations

The intensification of wastewater production has resulted in serious pollution of surface and underground water resources, creating environmental hazards and posing risks to human health. Untreated or insufficiently treated wastewater is a source of pathogens, viruses, bacteria, and heavy metal ions that threaten public health. Different techniques have been developed to treat wastewater to safe limits, allowing it to be reused. Treatment methods include biological, chemical, physical, and combined systems and can be applied at micro, meso, or macro levels.

In addition, sustainable use of treated wastewater tends to be a viable substitute for freshwater irrigation in regions suffering from water scarcity and water pollution. Sanitized municipal wastewater offers a reliable supply for irrigation of all agricultural crops with no undesired side effects on the soil, plant, or human health, provided safety norms and procedures are followed. However, the application of wastewater irrigation along with the recycling of treated wastewater should be managed carefully to avoid health hazards [186, 195, 196].

Reduction of agrochemical pollution

Numerous consequences stem from the reliance on excessive agrochemical application in agriculture to augment productivity, with pollution and food contamination being two significant issues. Instances of groundwater human contamination by hazardous organic pollutants, including pesticides, antibiotics, and hormones, have been observed close to the sediment–water interface of aquifers, resulting in health risks to life. The end product of agrochemical pollution enters the food chain, causing serious human health issues. The contamination of soil by pesticides, heavy metals, and alkaloids from plant wastes negatively affects the quality of life. These issues can be mitigated through appropriate nanotechnology usage, such as nano-biosense, nano delivery systems of nutrients, nano-biosafety components, and prospects for nano-ecosystems, which can limit excess usage of agrochemicals, promote their efficient utilization, and create a pollution-free society.

Encouraging adoption of eco-friendly pest and disease management systems (i.e., biotechnology-based control agents, cultural methods, biological control agents, biochemical pesticides, and resistant/tolerant varieties) is essential, in addition to substituting synthetic pesticides with alternative materials. Offering economic incentives or financial subsidies for farmer adoption of such systems would motivate farmers to use them. Farmers should be educated about the benefits of moderate application of agrochemicals and cultivation of pesticide-free produce that receives better prices in the market [197, 120, 198].

Environmental risk assessment

(ERA) determines whether an action—e.g., releasing a transgenic crop—poses an environmental hazard or risk. The need for ERA arises from the precautionary principle, i.e., uncertainty warrants preventive action. Although risk is usually considered the likelihood of a hazard, those terms are frequently confused. For risk assessment, a hazard must first be identified through various technical, conceptual, or formal means. The next step assesses the intrinsic properties of the hazard and its level of exposure as a function of the anticipated action. Hazard classifications are general, often leading to assumptions and simplifications about risk levels; exposure estimates are usually based on exposure scenarios. Some hazards, risks, and uses are commonly deemed low or negligible, allowing relevant entries in the databases used to support ERA, which is often seen as a burden, not an opportunity.

The primary post-market monitoring method for transgenic crops consists of recommendations for confounding factors to be surveyed during official food chain controls near fields where such crops are grown. More specifically, ERA relates to the approval procedures of GM plants and plant products. The guiding principle is that differences between GM and conventional counterparts should be negligible or acceptable for a particular use, plant, or product—otherwise, an application is rejected.

Chapter - 13

Climate Change, Plant Stress, and Biotechnology

Climate change is among the major global challenges of the 21st century. It is anticipated to have dire consequences on biodiversity, ecosystems, food systems, and human health, thereby affecting the livelihood of hundreds of millions of people. A temperature increase of more than 2 °C is expected to change ecosystems beyond repair, resulting in species extinction. Climate change has already started affecting crop productivity, and its effects are expected to amplify in the future. Aquatic and terrestrial ecosystems are expected to undergo irreversible change due to ocean acidification and alterations in freshwater systems. Extreme climate events and changing biodiversity are likely to interfere with the functioning of ecosystems, which in turn will aggravate the adaptation and mitigation of climate change. Future primary production will depend on better land, soil, and water management, as well as land restoration. To meet global food demand, climate-smart agriculture will be needed to increase the yield of climate-sensitive crops, to make agriculture resilient to climate change, and to minimize greenhouse gas emissions from agriculture.

The influence of climate change on the growth and yield of food crops cannot be ignored, as every climate parameter has a direct or indirect effect on food crop production. Decreased agricultural productivity caused by climate change can lead to higher prices for food commodities and food insecurity among low-income populations that spend larger portions of their disposable income on food. According to the United Nations Food and Agriculture Organization, higher average global temperatures will contribute to an increased frequency and intensity of droughts, floods, cyclones, and hurricanes, and a rise in sea levels is expected to inundate coastal areas. Crop production will be affected by these restrictions as well as by a lack of water, high temperatures, and salinity. Therefore, in addition to increasing crop production to meet the rising population demand, a empirical and scientific approach should be adopted to help crops cope with the future climate scenario. A better understanding of molecular mechanisms involved in the response of crops to climate change stressors would enhance the development of more resistant varieties [199, 200, 201].

Climate change impacts on crops

Climate-related phenomena such as highest-ever recorded temperature, extreme precipitation events short time frame, floods, cyclones, drought, and salt-affected soils have dampened growth of food-grain production like pulses and oilseeds for many nations. The most severe challenge for agriculture is that the investments made to adapt to climate change for enhancing crop and horticultural production are often negated by extreme natural calamities across the .cropping areas. Irrigated areas from tube wells and canals became non-productive. Therefore, it is imperative to conduct detailed study on high-impact climatic phenomena that severely affect crops and works as a barrier for achieving food sufficiency. Heat stress, drought stress, salinity stress, and flooding stress are some of the high-impact, high-probability phenomena that are predicted to increase in frequency, scale, and severity due to climate change. During the past decade, India has not only got possibility for occurrence of these stresses separately but also for simultaneous occurrence of these stresses such as heat–drought, drought–salinity, drought–flooding, heat–salinity, heat–flooding, as well as drought–salinity–flooding stresses.

Climate change became a major challenge for crop production across the world. Rising temperatures, changing rainfall patterns, and extreme climate events cause heat stress, drought stress, flooding stress, and salinity stress in crops, resulting in reduced yield and crop loss to farmers. Climate change will affect crop yield and food production as well as the nutritional quality of crops. Heat stress during flowering and grain-filling stages is detrimental to crop yield and quality. Drought is one of the major constraints during the Kharif season in India. Most of the crops are sensitive to terminal drought.

Salinity and alkalinity are major problems in irrigated crop production. Crop losses due to complete submergence and partial flooding are severe in low-lying areas. Climate-resilient crops require an integrated breeding strategy that considers the interaction and response of different stresses in the same environment. Climate couldn't be controlled, but change could certainly be tackled [202, 203, 204, 202, 203, 204, 202, 203, 204].

Heat and drought stress tolerance

Drought and high temperature are two of the most significant abiotic stresses impacting crops. Climate change is expected to increase climate extremes, resulting in more frequent heat and drought-related yield losses. Genetic improvement for higher yields under heat and drought stress requires an understanding of the underlying mechanisms and genetic basis of these stress responses, especially at the molecular level. Elucidation of molecular response pathways and the associated stress-response networks will help identify important regulatory genes. The application of genome-wide association studies (GWAS) in screening populations with natural variability provides opportunities for identifying new alleles that can be transferred through marker-assisted breeding. Such approaches may help breeders generate and identify genes/alleles associated with heat and drought tolerance, improve stress tolerance in elite lines through marker-assisted breeding, and develop better adaptative crops for future climate challenges.

Drought stress adaptative mechanisms in plants at the morphological, physiological, and molecular level may thus involve reductions in leaf size, increased root-to-shoot ratio, enhanced stomatal control, osmotic adjustment, xylem development, and expression variation of drought-responsive genes. The identification of different quantitative trait loci (QTLs) associated with drought tolerance in different populations contributes significantly toward improving the tolerance of heat-sensitive parent lines in marker-assisted backcrossing programmes designed to rapidly improve elite lines. Future crop-breeding strategies for improved drought tolerance will focus on exploiting natural variation for greater precision in factor analysis, the use of multiple traits of interest in single mapping populations, and the combined deployment of populations using landrace germplasm sources. Understanding stomatal, root, and leaf traits and exploiting existing natural variations for acceptance by breeding communities should enhance success in breeding for drought-adaptive traits.

Salinity and flooding stress management

In the context of climate change, salinity and flooding stress have become increasingly relevant for crop productivity. Management strategies for saline soil and water include amending chemicals, suitable geographical positioning of crops, crop selection, and application of plant growth-promoting microbes to help ameliorate and enhance plant growth under salinity. For flood-prone areas, wetland rice varieties, flood-tolerant varieties (like those possessing the SUB1 locus), or enhancing the oxidative-stress resistance mechanisms during early flood stress and recovery are effective approaches for yield improvement. Transgenic and marker-assisted breeding programs, targeted to either flooding or salinity tolerance or both, are ongoing in rice as well as other crops. Identification of key molecular players involved in plant responses to submergence or salinity in the field will open up new avenues to engineer salinity- or flooding-tolerant crops via a combined approach of conventional breeding and biotechnological interventions.

In low-lying regions of flooding-prone river basins, floods are expected to create further difficult conditions for rice cultivation by submerging crops for longer periods during the critical stages of development. For these places, the use of flood-tolerant rice varieties is an accepted means of dealing with such a problem. More specifically, the use of varieties that can survive submergence stress for about ten days seems to offer hope for maintaining rice production. Crops are also likely to face flooding conditions during the rainy season. Recent progress made in the breeding of new submergence-tolerant rice varieties has opened doors toward potentially decreasing yield losses because of excessive inundation in low-lying areas. In other crops, marker-assisted breeding programs that screen for naturally occurring alleles for prolonged submergence tolerance are being developed.

Molecular stress response pathways

Climate change is expected to influence the productivity and stability of crops, primarily due to increased heat and/or drought stresses. Plants perceive these stresses and respond through distinct signalling pathways, leading to tolerance. The major signalling networks include Ca2+ signalling, cyclic adenosine monophosphate (cAMP) and cyclic guanosine monophosphate (cGMP) pathways, reactive oxygen species (ROS), nitric oxide (NO), mitogen-activated protein kinase (MAPK) cascades, and other signalling molecules such as jasmonate, ethylene, and abscisic acid (ABA). Enhanced tolerance to stress conditions can be achieved by genetic manipulation of genes associated with these signalling networks. Moreover, genes involved in these pathways can be directly or indirectly used for the development of climate-resilient crops through genome editing, old-fashioned mutagenesis, or breeding approaches.

Effective approaches for developing climate-resilient crops involve the integration of multiple biotic and abiotic stress tolerance-related traits within a single genotype or species. Breeding for stress adaptation will require an understanding of each generation's reaction to the reciprocal stress factors and their interaction with changes in ecosystem-generating factors. Gene expression studies and marker-assisted approaches will help incorporate various individual stress-related genes, quantitative trait loci, or major genes responsible for heat, drought, and salt tolerance simultaneously in crop improvement programmes. Targeting the combinatorial use of common principles of heat and drought and drought and salinity stresses will help develop improved breeding strategies. Moreover, multilocation evaluations over different seasons will identify crops, genotypes, or germplasm resources capable of sustaining productivity under the fields' extreme environments [205, 206, 207].

Climate-resilient crop development

Integrative breeding and management plans significantly bolster crop resilience to climate change. Heat, drought, salinity, or flooding stresses threaten productivity in multiple regions. Scientific research employs dedicated resources in the study of stress responses and tolerance development, and their integration into major staple crops, standard horticulture species, and yet-unaddressed foods has become a priority. Climate change impacts on crops cannot be reduced through breeding alone; complemented by effective management practices, successfully developed tolerant varieties facilitate greater food production and ensure food security, farmer welfare, and ecosystem services. Realization of that potential depends ultimately on integrating multiple strategies, spanning development of tolerant varieties, optimal resource allocation, and integrated management encompassing both biophysical reality and socio-economic conditions.

Climate change is a major threat to global food security, because rising temperatures accelerate development and shorten flowering and grain-filling periods; drought reduces availability of soil moisture; salinization of land and water sources decreases crop productivity; and flooding causes nutrient leaching and soil erosion and reduces cropping area. In addition to reducing productivity in low-latitude areas, it increases the risk of yield gaps in regions where such gaps have until now not been a concern. Aggravating these effects, extreme meteorological events are becoming more frequent and intense—heat and drought are shrinking the area of suitable land, while flooding is creating new unsuitable regions. Within the next 50 years, at least another 1.5 billion people are expected to be added to the world population. So-combined, these trends call for the urgent development of climate-resilient crops. Breeding of tolerant varieties alone cannot answer the challenge. Breeding and crop management must work hand in hand; otherwise, the potential of tolerance will remain unachieved, and the hoped-for benefits for farmers, consumers, and ecosystems will be unrealized [208, 209, 210].

Chapter - 14

Nanobiotechnology in Agriculture and Food Systems

Information, Communications, and Technology (ICT) and Nanotechnology have emerged as two of the most significant and promising fields of science and technology in recent years. The micro—which science and technology for such ICT use has been in nanotechnology. Nanotechnology is concerned with things (the major components) in-the-nano-scale and which can walk, see, smell or hear, and even die. Nanotechnology is often described as "science on a very small scale," and nanomaterials are defined as materials with structural features in the size range from 1 to 100 nanometers (1 nm = 10-9 m). Nanotechnology offers a range of new products in agricultural and food systems.

Most agricultural inputs, including chemicals, are very costly and difficult for farmers with small landholdings. Reduced doses of nano-fertilizers and nano-pesticides can help to maintain crop yields at an economical cost. Transporting food from one part to another is very difficult due to quality loss. Food safety is another major challenge. Nanotechnologies for food packaging will extend shelf-life, reduce storage requirements, and ensure food safety. Sensors for the detection of chemicals in agriculture, food products, and soil will help for monitoring poisonous chemicals at all endemic and inreal-time. Novel nanotechnologies are needed for the detection of POSG (Plants or Agri-products Spoilage Gene) for the prediction of spoilage in food and plant produced from vegetable-based waste. Nanobiotechnology has great potential to contribute to agricultural sustainability. However, the socio-economic and environmental consequences of these systems are yet to be fully understood. Research in these areas should therefore proceed with caution, and full risk assessments should accompany any developments [211, 212, 213].

Introduction to agricultural nanotechnology

The application of engineered nanomaterials in agriculture and related food systems holds great potential for enhancing crop productivity and quality, reducing food spoilage, and making analytical and sensing tools more accessible to smallholders, among other prospective benefits. Nanotechnology may also contribute to sustainable food systems by improving agricultural efficiency, bioavailability, and storage length, thereby reducing food wastage. While many nanoproducts are already in use, others are being developed and assessed for their benefits and potential unintended harms. Therefore, risk reduction and safety remain critical and should take into account the analysis of the entire life cycle of nanoproducts. Research outputs also point to widening societal acceptance of nanoproducts, at least when proper explanatory information is provided alongside products. Nanotechnology is considered a source of solutions to many challenges faced in agriculture, food safety, and food quality.

Nanotechnology innovation consists of processes or products involving nanomaterials defined as natural or engineered materials with one or more dimensions in the nanoscale size range (1 nm to 100 nm). Nanotechnology could cover a wide area such as precision medicine, health care, drug delivery, nano-optics, nano electronics, food safety, agriculture, environmental clean-up, water treatment technologies, and many advanced energy conversion and storage devices. Within agriculture, these nano-scale formulations could be deployed to provide a sustainable and eco-friendly approach in improving the crop productivity and plant health, better detection of pathological and pest infected fields, improving post-harvest shelf-life and food safety, developing the smart delivery systems, smart packaging materials, food quality evaluation, data sensing, smart irrigation and bioremediation and phytoremediation development techniques [214, 215, 216].

Nano-fertilizers and nano-pesticides

Agricultural nanotechnology encompasses the use of nanomaterials, engineered and modified at the atomic or molecular level with a size ranging between 1 and 100 nm, for improving both the quantity and quality of agricultural production. The application of nanotechnology can be a revolution in crop production and protection. Nanotechnology offers a new technology platform for the development of nano-fertilizers and nanofertilizer-coated slow-release and/or controlled-release fertilizers for higher efficiency, pollution-free application and enhancement of fertility of various soil types. Nanoparticles causing toxicity in microorganisms and plants require proper management in the development of nanotechnology-based products. There is potential for nanotechnology to help solve current and future problems in agriculture, including the development of nano-microbiomes for safer and sustainable agriculture. These formulations have been developed for improved absorption, translocation and delivery of nutrients to plants. They provide a coherent means of getting nutrients into the plant where they're needed when they're needed while reducing leaching and contamination of the environment.

Nano-pesticides help reduce the quantity of pesticide used for crop protection and at the same time enhance its persistence. Nano-pesticides can be developed for controlled release and target delivery using formulated solid lipid nanoparticles, nanoemulsions, nanostructured lipid carrier systems, nanosuspensions, nanostructured microparticles, self-assembled polymeric nanoparticles or nanocapsules. Reducing the volume of active ingredient in nano-pesticides lessens the impact on nontarget organisms including insects and humans, while the nanoscale formulation generally allows for a higher degree of control over application location, time and concentration [217, 218, 219].

Nano-based sensors for plant health

Research into nano-based sensing technologies for real-time plant health monitoring continues to expand rapidly. Conventional plant disease monitoring methods often require onsite sample processing for laboratory diagnosis, which can take days and result in the spread of disease. In comparison, biosensor-mediated detection can provide fast and accurate identification using specific probes, and portable and easy-to-use devices are now available. Fiber-optic sensors offer a flexible architecture with the capacity for infield multiplexing and integration with wireless data-transferring systems. A wide range of nanomaterials producing various kind of signals (e.g. fluorescence, surface plasmon resonance, impedance, etc.) have been successfully applied in the detection of plant pathogens.

Optical and electrochemical biosensors using metal nanoparticles such as gold and silver have shown improved performance. These highly sensitive probes are capable of detecting pathogens at ultra-low concentrations, even at zeptomolar levels, and provide a feasible solution for early disease diagnosis onboard sensing. The use of carbon-based nanomaterials, especially graphene and carbon nanotubes, has also recently gained attention because of their high surface-area-to-volume ratio, excellent chemical properties, and biocompatibility [220, 221, 222].

Food packaging nanotechnologies

Nanotechnology opens innovative horizons in agriculture and food systems encompassing product delivery and packaging. Incorporation of nano-scale materials enhances the effectiveness of fertilizers, pesticides, growth regulators, and biological control agents to provide considerable benefits such as improved solubility, absorption, and mobility of active ingredients; controlled-release characteristics; reduced leaching; surface recognition by pathogens; and reduced rates of agrochemical applications. Nanotechnology has also paved the way for smart and bioactive packaging systems for food products through the incorporation of nanoparticles such as silver, zinc oxide, titanium dioxide, and natural polymer nanocomposites into packing materials. Incorporation of these nano-particles accelerates the preservation of food commodities by providing anti-bacterial, anti-fungal, anti-oxidative, and ethylene-scavenging properties, thereby prolonging shelf life.

Food packaging based on nanoscale materials supports safety, freshness, quality, and time-to-market while reducing losses. Nanosystems have superior functions due to the synergistic effect of different nanomaterials and agents with the capability of providing multiple functions in one platform. For example, multilayer nanocomposite films incorporating zeolites loaded with natural antimicrobial agents offer improved gas barrier properties, superior mechanical characteristics, and antimicrobial activity. Development of active packaging systems with oxygen-scavenging and ethylene-adsorbing properties, or capable of controlling moisture exchange and displaying gas-sensitive properties, further enhances preservation of food. Such novel technologies extend the useful life of food products while guaranteeing the safety and quality attributes of commodities destined for human consumption [223, 224, 225, 223, 224, 225].

Safety and regulatory concerns

Surrounding the use of nanobiosolutions in agriculture and food production have been, and remain, at the forefront of research. Although they are advantageous for different purposes, there are still questions regarding non-target-organism toxicity, environmental impact, and human health. These are generally related to the possibility of transport processes and crossings into living cells, in a manner similar to drugs, resulting in the distinctive high toxicity associated with nanoparticles. As a consequence, nanosafety is presently a priority, and there is growing pressure to develop safety and risk-assessment methods for the many nanobiosolutions arriving on the market. This is necessary to ensure consumer confidence in new nanoproducts, supply chains, and the food industry. Analytical methods for characterizing the properties of each nanoformulation are also required. To address these issues, risk assessments for biotechnology, nanotechnology, and nanotoxicology must be integrated into a single approach.

A holistic strategy for the safety assessment of all kinds of engineered nanomaterials should therefore be adopted. This strategy should assess the dosimetric relations of all chemical forms inside animal, plant, and human cells, tissues, and organs—especially regarding the bioavailability of commercial forms for all possible exposure pathways. Such a strategy will enable a risk assessment of engineered nanomaterials in relation to their intended use across different fields, without the need for specific testing at destination. In addition to the sensitive detection of foodborne pathogenic microorganisms and food spoilage, it is also necessary to develop sensing devices to detect the presence of GMOs and quantify their concentrations in food products as a basis for safe trade between countries with different regulations regarding the production and use of GM foodstuffs.

Chapter - 15

Socio-Economic, Ethical, and Policy Aspects

The future role of biotechnology development in contributing to local, national, regional, and global equitable sustainable food security, making optimal use of the biotechnology tools combination for a particular agriculture, socio-economic, and political situation, is widely accepted. It is a public policy matter making the best use of the specific circumstances of a nation and/or a region. While biotechnology is expected to play a vital role in supporting sustainable food security for the increasing global population, it should not be seen as a panacea. High technology without social development will not change the lives of people. In the last decades, many biotechnology tools have been developed and published, available for use, but the translation of invention into innovation and action by people at the ground level is a major challenge for future sustainable agriculture and food security systems.

A major part of the public consider GM crops as risky and unsafe for the environment and human health. Such a perception may have arisen due to unforeseen environmental impacts reported after GM crops' commercialization, issues related to intellectual property rights (IPRs), ethical considerations in using living organisms for transgenic crop development, and lack of proper communication between scientists and society. Addressing such public concerns requires a deeper understanding of the underlying values, guidance by a set of societal virtues and good practices, and building a trustworthy society. Another area of concern in biotechnology is IPRs. Strong IPR protection is vital for economic growth. With patent laws being a necessity for encouraging investment in some fields of technology, it often leads to the exclusion of others from the benefits of such innovations [86, 226, 227, 228].

Public perception of biotechnology

Knowledge about agricultural biotechnology and GM crops is still limited among the general public. Inadequate understanding increases distrust toward new technologies and products like genetically modified organisms (GMOs). Communication based on scientific evidence is essential to eliminate misconceptions. Interventions targeting different audiences and stakeholders can stimulate positive views and enhance acceptance. Biotechnology research raises ethical concerns that must be addressed through public dialogue. Sound policies and regulations strengthen public confidence in biotechnology and BDA technologies, resulting in social, economic, and environmental benefits. Governments can play a vital role in transgenic adoption through appropriate policies that stimulate private research and development.

Public acceptance is fundamental for biotechnology development and application. Biotechnology communication should be clearer and more targeted to specific groups. Different techniques should be employed for each audience, modifying content to improve understanding and persuasion. It is essential to convey accurate information on innovative technologies to clarify misconceptions. The media has a major impact on public views. General journalists should have an adequate grasp of biotechnology fundamentals to orient their articles toward evidence-based science, politics, and economics to ensure a balanced presentation of the pros and cons.

Public perception of genetic modification technologies has changed since the first GM products were introduced. Research on communication has greatly expanded, shedding light on the reasons behind negative attitudes and suggesting ways of transforming opposition into acceptance. Carefully designed communication studies can help identify the necessary attributes to gain the trust of consumers and other sectors [229, 230, 231].

Ethical considerations in GM crops

The rapid development of diverse biotechnological and nano biotechnological applications in the food and agricultural sectors must be matched by growing public acceptance, especially for GMOs (genetically modified organisms). Many sociological and psychological studies have been conducted over the years to understand the barriers hindering the widespread approval of GM crops. Fears of technology and loss of control over the food chain are often driven by insufficient knowledge among consumers. Even though the approval of GM crops is supported by many scientists around the world, this remains largely unnoticed by the wider public. Therefore, an effective communication policy, combined with more education in the general population and school, is essential to promote a better understanding of GM technology. The controversies surrounding GM crops also encompass intellectual property rights and ethical issues. GM technology is owned privately and companies increase patent application and protection globally, preventing sharing and access to GM technology by developing countries and farmers. The availability of important discoveries for public communities is hindered and often access to useful GM technology is additional to any GM product.

Ultimately, GM crops represent a profound ethical dilemma for society. The ethical question includes the right for the researcher to develop new technological plant modifications. Society recognizes the right of researchers to investigate plant genetic modification possibilities, but it also proposes a general caution towards GM crops. Society allows risks of new technologies and accepts any changes in the environment, but at the same time offers to farmers a sense of protection and security against the inherent risks of food production. Therefore, any potential risk of GM technology must be taken into account and technologies should be kept in the public domain for the achievement of sustainable farming [68, 232, 233].

Intellectual property rights

An effective innovation ecosystem requires strong and balanced intellectual property (IP) rights that foster research and development (R&D) investments. Private-sector investments in agricultural biotechnology are often supported or even driven by patent protection. Broad and patent-free access to the biotechnology knowledge pool thus remains vital for promoting technology transfer, ensuring the affordability and availability of innovative products, and stimulating further innovation. A lack of access to biotechnological knowledge and innovations can directly hinder public-sector and private-sector R&D in developing countries, particularly in least developed countries where resources for R&D are practically absent. Failure to harness biotechnology in a sustainable manner would critically undermine governments' efforts to achieve food security and enter into a dynamic phase of growth.

Developing countries are crucial to addressing global food security. Over 75% of the world's poor and malnourished people live in these countries, and the vast majority is dependent on agriculture for their livelihoods. Strengthening agricultural sectors and stimulating rural economies, and concomitant increases in income and food demand, can lead to rapid growth that reduces poverty while ensuring food security. Investments in agricultural R&D are indispensable for strengthening agricultural sectors in developing countries. These investments have yielded high social returns and can help achieve poverty reduction in a cost-effective way [234, 235, 236].

Biotechnology policies and governance

Food biotechnology is a valuable and essential area of modern science that can unfailingly assist policies and governance, technology transfer, and amelioration of pressing food-security concerns. Food security, risk analysis, science regulation, biosafety, and public acceptance are crucial components of effective and socially accepted technology governance. Rapidly evolving precision breeding techniques, including genome editing (such as CRISPR/Cas) and synthetic biology, have instigated debates on food safety, environmental impacts, ethical concerns, and the adequacy of existing regulations.

Governments are becoming increasingly aware of the potential socio-economic benefits of new approaches and seek to avoid excessive regulation that would prevent sound technologies from being developed and deployed. Successful technology transfer in food biotechnology requires understanding the special interests of developing countries, awareness of breeding priorities mandated by consumer demands, and involvement of local partners in research capacity development. Nevertheless, real transfer of the best transgenic technologies may largely remain for the future, when teaching and research resources can be allocated specifically to GM-enabled genetic improvement. Clearly, guidance on expectations and directions for food biotechnology transfer to developing countries is crucial [237, 238, 239].

Technology adoption in developing countries

Involves complex interactions among government policies, private-sector initiatives, and farmers' choices. Barriers to technology adoption can be classified into public policy-induced constraints (government policies, support programs, etc.), structural constraints (such as availability of land and capital), market imperfections and other supply-side constraints, risk and uncertainty factors, and socio-cultural considerations. Enabling factors include demand-pull market opportunities, proximity to urban markets, business-friendly policy, opening up of international markets, public programs that lower risks or uncertainties associated with natural hazards, availability of infrastructure, sound rules of the game (in relation to property rights, etc.), and a vibrant private promotional and support industry. Decentralized trials, on-farm demonstrations, participatory technology development, start-up assistance grants, local marketing support, availability of irrigation water, and access to production credit are the major factors contributing to farmers' demand for new technology in the region.

The integration of bio and nanotechnologies capable of producing affordable, accessible, and nutritious foods with adequate safety and quality must be fostered, and risk assessments undertaken to put in place appropriate regulations to allow for their successful commercialization and use. In countries such as India with specific climates and food habits, encouraging public-private partnerships is vital in overcoming difficulties in the bio/nanotechnology sphere. Development of genetically modified varieties of non-food crops such as the cotton produced worldwide with Bt technology is an encouraging sign for developing countries. There is an increasing demand and potential for both public-sector-led developments in food crops and private-sector-led efforts in non-food plants [240, 241, 242].

Chapter - 16

Future Trends and Integrated Approaches

The future of agriculture lies in a synergistic combination of agri-biotechnology with digital advances such as AI, omics technologies, and systems biology. Digital agriculture refers to techniques, tools, and services that use digital information and technology to collect, exchange, analyze, and transfer information. This digital information can improve producer decision-making by providing better agronomic science about field variability, allowing more precise inputs and management practices to increase productivity. Satellite-linked systems and drones can fine-tune in-field applications, improving efficiency and lowering costs, while AI can improve discovery and predictions and accelerate the pace of innovation in biotechnology.

Recent advances in omics technologies are generating massive datasets covering transcriptomics, proteomics, or metabolomics and providing unprecedented traits for plant breeders. Integrative analysis, bringing together multiple facets of life sciences, is opening new pathways for relationships with food systems at whole systems and food chain levels. Systems biology goes a step further and employs an evolving fusion of biology, technology, mathematics, and information science to model and predict how an organism or system behaves.

Food demand will be met only when integrated sustainable agri-food systems are designed and crafted. These systems can jointly meet multiple demands, including the delivery of healthy foods for human well-being, environmental conservation, climate-resilient ecosystem services, and economic prosperity of rural communities. Current challenges call for a co-benefit approach; trade-offs, even when essential, need to be minimized. The United Nations Food and Agriculture Organization and International Fund for Agricultural Development point to a vision of integrated sustainable agri-food systems as comprising the interlinked aspects of sustainability—social equity, economics, the environment, culture, and technology.

Digital agriculture and biotechnology

Digital agriculture incorporates modern technologies into food systems. Sensors, satellite imaging, drones, and Big Data enhance productivity and sustainability. These methods intersect with biotechnology, embracing the latest advancements.

Digital agriculture refers to using modern technologies—such as sensors, satellite imaging, mapping, drones, and Big Data—in agricultural production and the entire supply chain, from the farm to the consumer. These capabilities bring new efficiencies and risk reductions. Several technologies contributing to digital agriculture operate through the Internet of Things (IoT), by enabling real-time monitoring with remote sensors, devices, satellites, robots, and drones, creating an Internet of Things (IoT) system to address and resolve a wide range of problems. The use of satellite imaging, its integration with data from sensors installed in agricultural fields (weather station data, drone-acquired remote sensing images, etc.), and the progress made in the fields of Big Data and the Farm Management Information System resource allow the sharing, integration, analysis, and dissemination of information quickly and accurately, thereby guiding various production and management activities effectively.

Digital agriculture involves the application of various modern advanced technologies related to areas such as the Internet of Things, satellite remote sensing, geomatics, Big Data analysis, artificial intelligence, and Intelligent Robots in the production process of agriculture, forestry, animal husbandry, fishery, and the entire supply chain from the farm to the consumer. Digital agriculture also refers to the targeted, accurate prediction, judgment, control, and awareness of the state of plants and animals in the production process and surrounding environment by using related information technologies and controlling systems in a real-time or non-real-time manner. Digital agriculture promotes the efficiency and sustainable development of the productive process of agriculture, forestry, livestock, and fisheries. These rapid developments in the field of digital agriculture make increasing use of the latest biotechnology, with references from molecular breeding techniques and genomic editing technologies.

AI and omics technologies

Advances in biotechnology and Big Data have made it possible to efficiently address various challenges in agri-food systems while reducing costs within a short time frame. Data-centric technologies, Artificial Intelligence (AI), and omics technologies—genomics, transcriptomics, proteomics, metabolomics, and others—help in faster understanding of these complex biological systems. AI plays a prominent role in the whole agri-food chain, from identifying a trait of interest to monitoring and predicting climate smart–agriculture, disease, pest, yield forecasts, and storage conditions. AI also helps in precise and rapid synthesis of desired traits. Furthermore, the use of omics technologies with biotechnology techniques (genomics-assisted marker development, gene characterization, genomic selection, etc.) allows for speedier and more effective transfer of desired traits through Marker-Assisted Selection and simple hybridization in seed production. Using omics, Climate-Smart Agricultural interventions can be explored in layman's language.

The converging use of AI, Big Data, and omics technologies with biotechnology at various levels of crop improvement programming—from ideotyping to ideotype development and release of climate-resilient varieties—can address multiple upcoming challenges and threats of climate change, including the fundamental aspects of food quality and safety. Can help agriculture achieve its goal of becoming a zero-carbon emitting sector, while also giving maximum deliverables to the farming community.

Systems biology for food security

Integrated and data-driven approaches are increasingly needed to enable sustainable, resilient, and healthy agri-food systems. Systems biology can provide a connection between digital agriculture and biotechnology, generating new insights for discovery, development, and decision support. The growing reliance on big data and predictive models, together with emerging technologies in artificial intelligence and omics, will fuel an era of digital agriculture. Natural biophysical resources are finite, yet advanced biotech tools and techniques have the potential to introduce a second green revolution that reduces scarcity while liberating biodiversity. Artificial intelligence, especially deep learning, advances the use of phenomics and incorporates other forms of omics, including genomics, transcriptomics, metabolomics, and proteomics, to accelerate and improve the precision of trait discovery, prediction, and selection. In combination, these digital technologies are paving the way for more sustainable developments along the agri-food systems pathway, yet they will not guarantee success unless supported by appropriate governance frameworks.

Digital agriculture and biotechnology can thus leverage much deeper systems-based understanding to deliver on sustainable food security objectives—but not without strong accompanying governance measures. Like the first green revolution, too far a distance between innovation and application can lead to a tragic loss of public trust in both technologies, undermining their potential contribution to sustainable development; stakeholder engagement must remain an intrinsic component of both societal exploration of ethical issues and regulatory oversight of new products and breeder-friendly innovation frameworks. An integrative strategy that values digital, genome-scale, and traditional breeding technologies in combination offers the best hope of meeting growing demand amid shrinking resources while safeguarding natural biophysical capital and ecosystem integrity.

Integrated sustainable agri-food systems

The aspiration for sustainable food security is rapidly rising on the global agenda. Individual goals related to the food system overlap with broader ideals of sustainability. Sustainable Integrated Agri-food Systems (SIAS) can be defined as: the interaction of crops, livestock, fisheries and aquaculture, Apiculture, and food processing within a socially equitable, economically viable, worker safe, and environmentally responsible producing landscape that ensures food security, nutrition, and food safety for all; and contributes to the sustainable development of the economy and the creative relief of poverty within an equitable distribution of resources, capacities, and opportunities. These descriptions suggest that sustainable and resilient food production systems are to be developed for agricultural systems at all scales, from smallholders to large producers, and look holistically at all food systems while aiming to preserve and enhance the environment and sustain natural resources for present and future generations.

At the heart of the desire for effective SIAS is the requirement to move from trade-off decision-making to a systems perspective in which desirable outcomes in one or more sectors are not achieved to the detriment of other sectors. The potential for synergy between different components of the system must be harnessed as cannot the negative impacts of other agricultural-associated activities on poverty alleviation, food security, wellbeing, and the environment. Thus central to the development of SIAS and food security as a whole is the accurate prioritization, coordination, and incorporation of five factors within future planning and action—all of which must operate simultaneously and in synergy.

Vision for future sustainable food security

The need to safeguard global food security is urgent and the evidence for integrating advancements in biotechnology with other innovative approaches is overwhelming. Such evidence extends to the digital domain, leveraging digital data and information, artificial intelligence, big data, and – importantly – omics technologies. These developments yield new and transformational pathways to improve food security, inclusive of the capacity to meet future needs. Information-driven approaches will provide a wealth of information that can be fed into systems biology tools to generate models for food systems development, inform forecasting, aid in strategic decision-making, and support integrated approaches. The addition of second-generation gene-editing technologies to the biotechnology toolbox not only expands the scope for improvement, but also offers the tantalising possibility of working with breeding tools/selections through genome-editing approaches that are free of transgenic inheritance.

The application of the latest biotechnology techniques offers integrated approaches that support traditional breeding for increased food production and food quality in a sustainable manner while also maintaining the scope for expanding agricultural land. This is particularly true for large regions in Asia and Africa. Supporting this integrated application is in line with public policy-driven needs for sustainability, as expressed in international protocols and policies on climate, biodiversity, and environmental safety and sustainability.

Conclusion

The quest for sustainable food security in an evolving world is a challenge that no country can ignore, even though developing countries face the greatest obstacles. Modern agricultural biotechnology offers many solutions across a range of fundamental and applied research areas that contribute to achieving food security by increasing the quantity and quality of healthy food. The usefulness of biotechnology can be conveniently illustrated through the lens of several Sustainable Development Goals (SDGs) where an impact is expected and where targeted investments can pay off. The SDGs relate to the demands of a growing world population with increasingly diverse dietary needs and the threat posed by climate change to food production systems.

Food security is closely linked to the health of the plants that provide food. Healthy plants convey taste, character, freshness, and nutritional value. The interaction of plant health and food systems can only be beneficial, and agri-biotechnology can be a strong ally in obtaining healthy plants. Well-maintained healthy crops are likely to produce more and better quality food in terms of both nutrition and safety, thereby providing resilience to fluctuating stresses such as economic crises, pandemics, and climate change. Hence, plant health is a fundamental requirement for a sustainable and resilient food system."

References

1. A. Poblacion, S. E. De Cuba, and J. T. Cook, "For 25 years, food security has included a nutrition domain: is a new measure of nutrition security needed?," *Journal of the Academy of Nutrition and Dietetics*, vol. 122, no. 12, pp. 2290-2298, 2022. jandonline.org
2. N. Adhikari, M. Adhikari, N. Shrestha, "Nutrition and food security in Nepal: a narrative review of policies," *Nutrition*, vol. 2023. oup.com
3. M. K. Sharif, K. Sarwar, N. Abid, et al., "Food Security, Food Safety, and Sanitation," in *Food Security in the …*, 2024. [HTML]
4. R. FOOD and H. D. M. AFFORDABLE, "Food security and nutrition in the World," 2022. fao.org
5. W. Health Organization, "The state of food security and nutrition in the world 2022: Repurposing food and agricultural policies to make healthy diets more affordable," 2022. google.com
6. T. Burki, "Food security and nutrition in the world," The Lancet Diabetes & Endocrinology, 2022. thelancet.com
7. A. H. Wudil, M. Usman, J. Rosak-Szyrocka, and L. Pilař, "Reversing years for global food security: A review of the food security situation in Sub-Saharan Africa (SSA)," *International Journal of Environmental Research and Public Health*, vol. 19, no. 12, 2022. mdpi.com
8. J. Akram, N. Naeem, M. T. Manzoor, Q. Ali, "Role of modern biotechnology in improving crop protection," Bulletin of Biological, 2025. bbasr.org
9. S. Das, M. K. Ray, D. Panday, "Role of biotechnology in creating sustainable agriculture," PLOS Sustainability and …, 2023. plos.org

10. T. Sinha, A. Sharma, A. Das, and A. Kumar, "The impact of biotechnology in shaping the modern agriculture," *... & Biotechnology*, 2024. researchgate.net
11. M. Nawaz, J. Sun, S. Shabbir, W. A. Khattak, and G. Ren, "A review of plants strategies to resist biotic and abiotic environmental stressors," *Science of The Total Environment*, vol. 2023, Elsevier. [HTML]
12. R. Balestrini, W. Chitarra, A. Ghirardo, A. Nardini et al., "A stressful life: How plants cope with multiple biotic and abiotic adverse factors," Plant Stress, 2022. units.it
13. Z. Shan, S. Zhou, A. Shah, Y. Arafat, and S. A. H. Rizvi, "Plant allelopathy in response to biotic and abiotic factors," Agronomy, 2023. mdpi.com
14. R. Raman, H. H. Lathabai, and P. Nedungadi, "Sustainable development goal 12 and its synergies with other SDGs: identification of key research contributions and policy insights," Discover Sustainability, 2024. springer.com
15. A. A. Adesoji, J. Ade-Omowaye, A. Afolalu, et al., "Waste to Wealth: Engineering Solutions for SDG 12," in *Proceedings of the IEEE Conference on Engineering and Business for Sustainable Development*, 2024. [HTML]
16. M. M. K. Akter, U. N. Haq, M. M. Islam, and M. A. Uddin, "-apparel manufacturing and material waste management in the circular economy: A conceptual model to achieve sustainable development goal (SDG) 12 for …," Cleaner Environmental, vol. 2022, Elsevier, 2022. sciencedirect.com
17. E. González-Domínguez, T. Caffi, V. Rossi, "Plant disease models and forecasting: changes in principles and applications over the last 50 years," Am. Phytopath. Soc., 2023. apsnet.org
18. J. Singh, B. Chhabra, A. Raza, and S. H. Yang, "Important wheat diseases in the US and their management in the 21st century," Frontiers in Plant Science, vol. 2023. frontiersin.org
19. A. Kumar, S. K. Middha, S. V. Menon, B. Paital, and S. Gokarn,

"Current challenges of vaccination in fish health management," Animals, vol. 14, no. 1, 2024. mdpi.com

20. T. Daszkiewicz, "Food production in the context of global developmental challenges," Agriculture, 2022. mdpi.com
21. [21, 1] Interagency Agricultural Projections Committee, "USDA Agricultural Projections to 2034," 2025. umn.edu
22. W. Health Organization, "The state of food security and nutrition in the world 2022: Repurposing food and agricultural policies to make healthy diets more affordable," 2022. google.com
23. J. Zhou, X. Zhang, Z. Qu, C. Zhang, F. Wang, T. Gao, and Y. Yao, "Progress in research on prevention and control of crop fungal diseases in the context of climate change," Agriculture, 2024. mdpi.com
24. Y. Gai and H. Wang, "Plant disease: A growing threat to global food security," Agronomy, 2024. mdpi.com
25. N. Mehmood, M. Saeed, S. Zafarullah, S. Hyder, "Multifaceted Impacts of Plant-Beneficial Pseudomonas spp. in Managing Various Plant Diseases and Crop Yield Improvement," ACS Publications, 2023. acs.org
26. Z. Liu, A. Lv, and T. Li, "Intensified Drought Threatens Future Food Security in Major Food-Producing Countries," Atmosphere, 2024. mdpi.com
27. P. K. Krishnamurthy R, J. B. Fisher, R. J. Choularton, et al., "Anticipating drought-related food security changes," *Nature*, 2022. google.com
28. M. T. I. Khan, S. Anwar, and Z. Batool, "The role of infrastructure, socio-economic development, and food security to mitigate the loss of natural disasters," *Environmental Science and Pollution Research*, vol. 2022, Springer. researchgate.net
29. C. Tidiane Ndour, W. Diop, and S. Asongu, "The effect of natural disasters on food security in Sub-Saharan Africa," Social Responsibility Journal, 2025. emerald.com

30. A. Abohajeb and H. Aldhlea, "The complex humanitarian crisis in Yemen: the story of man-made food insecurity and potential famine," Handbook on Humanitarian Crises, 2025. [HTML]

31. S. Ezrari, I. Legrifi, M. Taoussi, M. Khadiri, "Plant–pathogen interactions and global food security," in *Pathogen Interaction*, 2024, Springer. [HTML]

32. B. K. Singh, M. Delgado-Baquerizo, E. Egidi, et al., "Climate change impacts on plant pathogens, food security and paths forward," *Nature Reviews*, 2023. nih.gov

33. A. Hafeez, B. Ali, M. A. Javed, A. Saleem, M. Fatima, A. Fathi, et al., "Plant breeding for harmony between sustainable agriculture, the environment, and global food security: an era of genomics-assisted breeding," *Planta*, vol. 2023, Springer. researchgate.net

34. G. Albahri, A. A. Alyamani, A. Badran, A. Hijazi, M. Nasser, et al., "Enhancing essential grains yield for sustainable food security and bio-safe agriculture through latest innovative approaches," Agronomy, 2023. mdpi.com

35. M. Noman, T. Ahmed, U. Ijaz, A. Hameed, "Microbe-oriented nanoparticles as phytomedicines for plant health management: an emerging paradigm to achieve global food security," Reviews in Food, vol. 2023, Taylor & Francis. google.com

36. S. Kumar, M. Choudhary, K. J. Reddy, "A review on the impact of climate change on plant pathogen interactions," J. Adv., 2024. researchgate.net

37. J. H. J. Leveau, "Re-envisioning the plant disease triangle by integration of host microbiota and a pivot in focus to health outcomes," Annual Review of Phytopathology, 2024. annualreviews.org

38. V. Gorshkov and I. Tsers, "Plant susceptible responses: the underestimated side of plant–pathogen interactions," Biological Reviews, 2022. wiley.com

39. O. G. Tomilova, N. A. Kryukova, M. V. Efimova, et al., "The Endophytic Entomopathogenic Fungus Beauveria bassiana

Alleviates Adverse Effects of Salt Stress in Potato Plants," Horticulturae, 2023. mdpi.com

40. YB Yang, C Yang, JR Zheng, and LZ Xu, "Chloride salt enhances plant resistance to biotic stresses," Frontiers in Plant Science, 2024. frontiersin.org
41. B. Baran, F. Ölmez, B. Çapa, and M. Dikilitas, "Defense Pathways of Wheat Plants Inoculated with Zymoseptoria tritici under NaCl Stress Conditions: An Overview," Life, 2024. mdpi.com
42. A. Ali, M. Shahbaz, F. Ölmez, N. Fatima, "RNA interference: a promising biotechnological approach to combat plant pathogens, mechanism and future prospects," *World Journal of …*, 2024. proquest.com
43. S. Akbar, Y. Wei, and M. Q. Zhang, "RNA interference: promising approach to combat plant viruses," International Journal of Molecular Sciences, 2022. mdpi.com
44. I. T. Bocos-Asenjo, J. Niño-Sánchez, M. Ginés, and others, "New insights on the integrated management of plant diseases by RNA strategies: Mycoviruses and RNA interference," *International Journal of …*, 2022. mdpi.com
45. R. Chen, K. Gajendiran, and B. B. H. Wulff, "R we there yet? Advances in cloning resistance genes for engineering immunity in crop plants," Current opinion in plant biology, 2024. sciencedirect.com
46. H. Zhang, J. Huang, and Y. Huang, "Identification and characterization of plant resistance genes (R genes) in sorghum and their involvement in plant defense against aphids," Plant Growth Regulation, 2022. researchgate.net
47. P. Sun, X. Han, R. J. Milne, and G. Li, "Trans-crop applications of atypical R genes for multipathogen resistance," Trends in Plant Science, 2024. researchgate.net
48. Q. Liu, X. Jin, J. Cheng, and H. Zhou, "Advances in the application of molecular diagnostic techniques for the detection of infectious disease pathogens," *Molecular Medicine*, 2023. spandidos-

publications.com

49. J. E. Schmitz, C. W. Stratton, D. H. Persing, "Forty years of molecular diagnostics for infectious diseases," *Journal of Clinical Microbiology*, vol. 2022. asm.org
50. E. Gerace, G. Mancuso, A. Midiri, S. Poidomani, and S. Zummo, "Recent advances in the use of molecular methods for the diagnosis of bacterial infections," Pathogens, vol. 11, no. 5, 2022. mdpi.com
51. M. A. Pandit, J. Kumar, S. Gulati, N. Bhandari, and P. Mehta, "Major biological control strategies for plant pathogens," *Pathogens*, vol. 11, no. 5, 2022. mdpi.com
52. S. Tatineni and G. L. Hein, "Plant viruses of agricultural importance: Current and future perspectives of virus disease management strategies," Phytopathology®, 2023. apsnet.org
53. G. Li, L. An, W. Yang, L. Yang, T. Wei, J. Shi, and J. Wang, "Integrated biotechnological and AI innovations for crop improvement," *Nature*, 2025. [HTML]
54. T. B. Dos Santos, A. F. Ribas, S. G. H. de Souza, et al., "Physiological responses to drought, salinity, and heat stress in plants: a review," Stresses, 2022. mdpi.com
55. [55, 1] P. B. Angon, M. Tahjib-Ul-Arif, S. I. Samin, and U. Habiba, "How do plants respond to combined drought and salinity stress?—A systematic review," Plants, vol. 2022. mdpi.com
56. S. Alghamdi, "Drought and salinity effects on plant growth: a comprehensive review," SABRAO J Breed Genet, 2024. sabraojournal.org
57. D. S. T. Nicholl, "An introduction to genetic engineering," 2023. uclv.edu.cu
58. Y. Yan, X. Zhu, Y. Yu, C. Li, and Z. Zhang, "Nanotechnology strategies for plant genetic engineering," *Advanced Materials*, vol. 34, no. 12, 2022. [HTML]
59. W. Su, M. Xu, Y. Radani, and L. Yang, "Technological development and application of plant genetic transformation,"

International Journal of Molecular, vol. 2023. mdpi.com

60. A. KhokharVoytas, M. Shahbaz, and M. F. Maqsood, "Genetic modification strategies for enhancing plant resilience to abiotic stresses in the context of climate change," *Functional & Integrative Genomics*, vol. 2023, Springer. [HTML]
61. R. M. Shelake, U. S. Kadam, R. Kumar, D. Pramanik, and others, "Engineering drought and salinity tolerance traits in crops through CRISPR-mediated genome editing: Targets, tools, challenges, and perspectives," *Plant*, vol. 2022. cell.com
62. D. Trono and N. Pecchioni, "Candidate genes associated with abiotic stress response in plants as tools to engineer tolerance to drought, salinity and extreme temperatures in wheat: an …," Plants, 2022. mdpi.com
63. M. Ahmed, M. Naeem, Y. Zeng, and M. A. R. Rashid, "Genome-wide association mapping for high temperature tolerance in wheat through 90k SNP array using physiological and yield traits," *Plos One*, vol. 2022. plos.org
64. D. Shahi, J. Guo, S. Pradhan, M. Avci, G. Bai, J. Khan, "Genome-Wide Association Study and Genomic Prediction of Soft Wheat End-Use Quality Traits Under Post-Anthesis Heat-Stressed Conditions," Biology, vol. 2024. mdpi.com
65. Y. Ahmed, Y. Zeng, M. A. Khan, M. A. R. Rashid, and others, "Genome-wide association mapping of bread wheat genotypes using yield and grain morphology-related traits under different environments," *Frontiers in …*, 2023. frontiersin.org
66. K. S. Sumanth, T. Anusha, and S. Prakash, "Transgenic crops: present status, problems and future prospects," Pharma Innov J, 2022. academia.edu
67. N. Kumar, "Transgenic plants: methods and protocols," 2025. [HTML]
68. M. A. Aziz, F. Brini, H. Rouached, et al., "Genetically engineered crops for sustainably enhanced food production systems," *Frontiers in Plant Science*, vol. 2022. frontiersin.org

69. J. L. Domingo, "Genetically modified crops: balancing safety, sustainability, and global security," Environmental Research, 2025. sciencedirect.com

70. R. Thomas, "Legal Challenges in Biosafety of Transgenic Plants," Issue 6 Indian JL & Legal Rsch., 2022. [HTML]

71. B. Mahanayak, "Ensuring Biosafety of Genetically Modified Organisms (GMOs): Regulatory Frameworks and Risk Assessments in India," researchgate.net, . researchgate.net

72. T. P. A. Krishna, D. Veeramuthu, T. Maharajan, "The era of plant breeding: Conventional breeding to genomics-assisted breeding for crop improvement," *Current Science*, vol. 2023. nih.gov

73. M. Singh, U. Nara, A. Kumar, S. Thapa, and C. Jaswal, "Enhancing genetic gains through marker-assisted recurrent selection: from phenotyping to genotyping," Cereal Research, vol. 2022, Springer. [HTML]

74. M. Sheikh, F. Iqra, H. Ambreen, K. A. Pravin, M. Ikra, et al., "Integrating artificial intelligence and high-throughput phenotyping for crop improvement," *Journal of Integrative …*, 2024. sciencedirect.com

75. J. Y. Wang and J. A. Doudna, "CRISPR technology: A decade of genome editing is only the beginning," Science, 2023. science.org

76. T. Van Vu, S. Das, G. Hensel, and J. Y. Kim, "Genome editing and beyond: what does it mean for the future of plant breeding?," Planta, 2022. springer.com

77. L. Gilbertson, H. Puchta, and R. K. Slotkin, "The future of genome editing in plants," Nature Plants, 2025. kit.edu

78. C. Li, W. Chu, R. A. Gill, S. Sang, Y. Shi, X. Hu, et al., "Computational tools and resources for CRISPR/Cas genome editing," Genomics, 2023. oup.com

79. G. Liu, Q. Lin, S. Jin, and C. Gao, "The CRISPR-Cas toolbox and gene editing technologies," Molecular cell, 2022. cell.com

80. S. Wang, Z. Qu, Q. Huang, J. Zhang, S. Lin, and Y. Yang,

"Application of gene editing technology in resistance breeding of livestock," *Life*, vol. 12, no. 2, 2022. mdpi.com

81. M. L. Mueller and A. L. Van Eenennaam, "Synergistic power of genomic selection, assisted reproductive technologies, and gene editing to drive genetic improvement of cattle," CABI Agriculture and Bioscience, 2022. springer.com
82. G. Nerkar, S. Devarumath, M. Purankar, A. Kumar, "Advances in crop breeding through precision genome editing," Frontiers in…, 2022. frontiersin.org
83. D. Wray-Cahen, A. Bodnar, C. Rexroad, et al., "Advancing genome editing to improve the sustainability and resiliency of animal agriculture," CABI Agriculture and Bioscience, vol. 3, no. 1, 2022. springer.com
84. A. M. Dessie and Z. B. Zegeye, "Review on: Public perception of biotechnology on genetically modified crops, bio policy and intellectual property rights," *American Journal of Polymer Science*, 2024. researchgate.net
85. B. K. Ghimire, C. Y. Yu, W. R. Kim, H. S. Moon, J. Lee, and S. H. Kim, "Assessment of benefits and risk of genetically modified plants and products: current controversies and perspective," *Sustainability*, 2023. mdpi.com
86. A. Vega Rodríguez and C. Rodríguez-Oramas, "Myths and realities about genetically modified food: A risk-benefit analysis," *Applied Sciences*, 2022. mdpi.com
87. C. M. Galanakis, "The future of food," Foods, 2024. mdpi.com
88. A. Polidoros, I. Nianiou-Obeidat, N. Tsakirpaloglou, "Genome-editing products line up for the market: will Europe harvest the benefits from science and innovation?" Genes, 2024. mdpi.com
89. S. K. Niazi, "The Dawn of in vivo gene editing era: A Revolution in the making," Biologics, 2023. mdpi.com
90. A. Tuncel, C. Pan, T. Sprink, R. Wilhelm, "Genome-edited foods," *Nature Reviews*, 2023. nsf.gov

91. T. Aronen, S. Varis, and M. Tikkinen, "Somatic embryogenesis: concept, principles, and applications," Forest Microbiology, 2025. [HTML]

92. M. Elhiti and C. Stasolla, "Transduction of signals during somatic embryogenesis," Plants, 2022. mdpi.com

93. M. Ramakrishnan, M. Zhou, S. A. Ceasar, D. J. Ali, "Epigenetic modifications and miRNAs determine the transition of somatic cells into somatic embryos," Plant Cell Reports, 2023. [HTML]

94. M. D. Bogdanović and K. B. Ćuković, "Secondary Somatic Embryogenesis in Plants: From Cellular Mechanisms to Biotechnological Potential," Plants, 2025. mdpi.com

95. N. Abdalla, H. El-Ramady, M. K. Seliem, and M. E. El-Mahrouk, "An academic and technical overview on plant micropropagation challenges," Horticulturae, vol. 2022. mdpi.com

96. G. A. Babu, K. Mosa Christas, E. Kowsalya, et al., "Improved sterilization techniques for successful in vitro micropropagation," in *scale tissue culture for*, Springer, 2022. [HTML]

97. S. Gupta, A. Singh, K. Yadav, and N. Pandey, "Micropropagation for multiplication of disease-free and genetically uniform sugarcane plantlets," in *Plant Tissue Culture*, 2022, Elsevier. [HTML]

98. N. Sharma, N. Kumar, J. James, "Strategies for successful acclimatization and hardening of in vitro regenerated plants: Challenges and innovations in micropropagation techniques," Plant Science Today, vol. 2023. semanticscholar.org

99. P. P. Behera, K. Sivasankarreddy, and V. Prasanna, "Somatic embryogenesis and plant regeneration in horticultural crops," in *… and plantation crops*, 2022, Springer. [HTML]

100. J. Björs, A. Tudoran, D. Gräns, "Clonal propagation of conifers by somatic embryogenesis (SE)–an introduction to methodology and examples of applications for research and plant production," 2025. reforestationchallenges.org

101. S. Abbasi, "Plant–microbe interactions ameliorate phosphate-

mediated responses in the rhizosphere: a review," Frontiers in Plant Science, 2023. frontiersin.org

102. A. Yadav and K. Yadav, "Regulation of plant-microbe interactions in the rhizosphere for plant growth and metabolism: Role of soil phosphorus," Phosphorus in Soils and Plants, 2024. intechopen.com

103. H.A. Pantigoso and D. Newberger, "The rhizosphere microbiome: Plant–microbial interactions for resource acquisition," *Journal of Applied …*, 2022. oup.com

104. R. Krishna, W. A. Ansari, K. Khandagale, A. P. Benke, et al., "Meristem culture: a potential technique for in vitro virus-free plants production in vegetatively propagated crops," Advances in Plant Tissue Culture, vol. 2022, Elsevier. [HTML]

105. L. L. Rodríguez-Verástegui, C. Y. Ramírez-Zavaleta, et al., "Viruses infecting trees and herbs that produce edible fleshy fruits with a prominent value in the global market: An evolutionary perspective," *Plants*, vol. 2022. mdpi.com

106. Z. Zhang, Y. Hu, M. Wang, R. Nie, M. Sun, Z. Xie, "Regeneration of virus-free plants from undeveloped ovules of seedless citrus cultivars: a practical approach for combating citrus viral diseases," Horticulture, vol. 2024, Springer. springer.com

107. J. FTA, N. Orynbek, A. Abduraimova, and others, "Biotechnological production of 2- phenylethanol from agroindustrial byproducts: experimental evaluation, techno- economic analysis, and life cycle assessment," Biofuels, Bioproducts and Biorefining, 2025. wiley.com

108. J. Zhang, S. Waldron, Z. Langford, and B. Julianto, "China's growing influence in the global carrageenan industry and implications for Indonesia," Journal of Applied…, vol. 2024, Springer. springer.com

109. J. Zhang, Z. Langford, and S. Waldron, "The global carrageenan industry," in *Globalisation and livelihood …*, 2023. oapen.org

110. A. K. Tiwari, "IPM essentials: combining biology, ecology, and

agriculture for sustainable pest control," Journal of Advances in Biology, 2024. msforpublish.com

111. PB Angon, S. Mondal, I. Jahan, M. Datto, "Integrated pest management (IPM) in agriculture and its role in maintaining ecological balance and biodiversity," Advances in ..., vol. XX, no. YY, pp. ZZ, 2023. wiley.com

112. A. F. Bueno, W. P. Sutil, S. M. Jahnke, and G. A. Carvalho, "Biological control as part of the soybean integrated pest management (IPM): Potential and challenges," Agronomy, 2023. mdpi.com

113. M. Ahmed, A. Javeed, A. R. Sajid, S. Ullah, "Biopesticides: a healthy alternative of hazardous chemical pesticides, current development and status in China," Biomedical ..., 2022. researchgate.net

114. M. S. Ayilara, B. S. Adeleke, S. A. Akinola, et al., "Biopesticides as a promising alternative to synthetic pesticides: A case for microbial pesticides, phytopesticides, and nanobiopesticides," Frontiers in ..., 2023. frontiersin.org

115. G. M. Daraban, R. M. Hlihor, and D. Suteu, "Pesticides vs. biopesticides: From pest management to toxicity and impacts on the environment and human health," Toxics, 2023. mdpi.com

116. T. R. Glare and L. M. L. Nollet, "Types of biopesticides," Biopesticides handbook, 2023. [HTML]

117. L. M. L. Nollet, "Metabolism of Biopesticides," Biopesticides Handbook, 2023. [HTML]

118. X. Yao, H. Guo, K. Zhang, M. Zhao, J. Ruan, "Trichoderma and its role in biological control of plant fungal and nematode disease," *Frontiers in Microbiology*, 2023. frontiersin.org

119. M. Boro, S. Sannyasi, D. Chettri, and A. K. Verma, "Microorganisms in biological control strategies to manage microbial plant pathogens: a review," Archives of microbiology, 2022. [HTML]

120. D. K. Jaiswal, S. J. Gawande, P. S. Soumia, and R. Krishna,

"Biocontrol strategies: an eco-smart tool for integrated pest and diseases management," BMC Microbiology, vol. 22, no. 1, 2022. springer.com

121. Y. Rezaee Danesh, J. M. Mulet, and R. Porcel, "Bridging microbial biocontrol and phytochemical biopesticides: Synergistic approaches for sustainable crop protection," Plants, 2025. mdpi.com

122. A. R. Sheoran, N. Lakra, B. S. Saharan, A. Luhach, et al., "Enhancing plant disease resistance: insights from biocontrol agent strategies," *Journal of Plant Growth*, vol. 2025, Springer. [HTML]

123. X. Liang, S. Yu, Y. Ju, Y. Wang et al., "Integrated management practices foster soil health, productivity, and agroecosystem resilience," Agronomy, 2025. mdpi.com

124. Y. Xing, X. Wang, and A. Mustafa, "Exploring the link between soil health and crop productivity," Ecotoxicology and environmental safety, 2025. sciencedirect.com

125. J. Suman, A. Rakshit, S. D. Ogireddy, S. Singh, "Microbiome as a key player in sustainable agriculture and human health," Frontiers in Soil, vol. 2022. frontiersin.org

126. G. R. Xavier, E. C. Jesus, A. Dias, M. R. R. Coelho, and Y. C. Molina, "Contribution of biofertilizers to pulse crops: from single-strain inoculants to new technologies based on microbiomes strategies," *Plants*, vol. 2023. mdpi.com

127. A. A. Otaiku, A. A. Soretire, and P. C. Mmom, "Biofertilizer Impacts on Soybean Cultivation, Humid Tropics: Biological Nitrogen Fixation, Yield, Soil Health and Smart Agriculture Framework," Int. J. Agric. Ext. Rural. Dev. Stud, 2022. academia.edu

128. K. L. Rana, D. Kour, T. Kaur, R. Negi, R. Devi, "Endophytic nitrogen-fixing bacteria: Untapped treasurer for agricultural sustainability," J. Appl. Biol., 2023. researchgate.net

129. A. Jalal, M. C. M. T. Filho, E. C. da Silva, "Plant growth-

promoting bacteria and nitrogen fixing bacteria: sustainability of non-legume crops," in *Nitrogen fixing bacteria*, 2022, Springer. researchgate.net

130. P. Djighaly, N. Diagne, E. Tournier, M. Ngom, "Beneficial and adverse effects of bio-inoculation on predicted functional microbial communities in salt-land restoration," Authorea, 2025. authorea.com

131. K. Prasad, "… L) Through Co-Inoculation of Novel Microbial Consortium Plant Growth Promoting Rhizobacteria, Glycoprotein Producing AM Fungi and Chemical Fertilizer …," Open Access Journal of Microbiology and …, 2022. researchgate.net

132. S. K. Goswami, A. S. Kashyap, R. Kumar, R. S. Gujjar, "Harnessing Rhizospheric microbes for eco-friendly and sustainable crop production in saline environments," Current..., vol. 2024, Springer. academia.edu

133. R. Husain, N. Vikram, S. Pandey, and G. Yadav, "Microorganisms: An eco-friendly tools for the waste management and environmental safety," Biotechnological, vol. 2022, Springer. researchgate.net

134. J. Bauza-Kaszewska, B. Breza-Boruta, G. Lemańczyk, "Effects of Eco-Friendly product application and sustainable agricultural management practices on soil properties and phytosanitary condition of winter wheat," Sustainability, 2022. mdpi.com

135. L. Wen, Y. Peng, Y. Zhou, G. Cai, Y. Lin, and B. Li, "Effects of conservation tillage on soil enzyme activities of global cultivated land: A meta-analysis," *Journal of Environmental Management*, 2023. sciencedirect.com

136. Y. H. Mir, M. A. Ganie, T. I. Shah, S. A. Bangroo, S. A. Mir, and others, "Soil microbial and enzyme activities in different land use systems of the Northwestern Himalayas," PeerJ, 2023. peerj.com

137. S. Sharma, B. Lishika, and S. Kaushal, "Soil quality indicators: A comprehensive review," *Journal of Plant & Soil*, 2023. msforpublish.com

138. G. Nziguheba, J. Adewopo, C. Masso, "Assessment of sustainable land use: linking land management practices to sustainable land use indicators," Sustainability, vol. 2022, Taylor & Francis. tandfonline.com

139. T. Alemu, D. Tolossa, F. Senbeta, "The effects of continuous sustainable land management practices on agricultural land productivity in Central Ethiopia," *Mining Lands Management*, 2023. academia.edu

140. N. Haregeweyn, A. Tsunekawa, M. Tsubo, et al., "Progress and challenges in sustainable land management initiatives: A global review," *Science of the Total Environment*, vol. 2023, Elsevier. sciencedirect.com

141. S. Świerczyński, Z. Zydlik, and T. Kleiber, "The influence of foliar nutrition of apple trees with silicon on growth and yield as well as mineral content in leaves and fruits," Agronomy, 2022. mdpi.com

142. H. K. Bons and A. Sharma, "Impact of foliar sprays of potassium, calcium, and boron on fruit setting behavior, yield, and quality attributes in fruit crops: a review," Journal of Plant Nutrition, 2023. [HTML]

143. T. Milošević and N. Milošević, "Role of nutrients in modifications of fruit quality and antioxidant activity," in *Plant Ionomics: Sensing, Signaling …*, 2023. [HTML]

144. S. M. Alomari, R. S. Hasan, A. N. Al-Najim, "Nitrogen-fixing Bacteria and their Applications in the Environment: A Review," *International Journal of …*, 2024. researchgate.net

145. A. M. Timofeeva, M. R. Galyamova, and S. E. Sedykh, "Plant growth-promoting soil bacteria: nitrogen fixation, phosphate solubilization, siderophore production, and other biological activities," Plants, 2023. mdpi.com

146. A. Fathi, "Role of nitrogen (N) in plant growth, photosynthesis pigments, and N use efficiency: A review," Agrisost ISSN 1025-0247, 2022. reduc.edu.cu

147. A. Singh, A. Hidangmayum, P. Tiwari, and B. N. Singh, "How the

soil nitrogen nutrient promotes plant growth—a critical assessment," *New and Future*, vol. 2022, Elsevier. [HTML]

148. D. Ma, W. Teng, Y. T. Mo, B. Yi, and W. L. Chen, "Effects of nitrogen, phosphorus, and potassium fertilization on plant growth, element levels in plants and soil, and the relationships among nutrient concentrations …," *Journal of Plant Nutrition*, 2024. [HTML]

149. A. Timofeeva, M. Galyamova, and S. Sedykh, "Prospects for using phosphate-solubilizing microorganisms as natural fertilizers in agriculture," Plants, 2022. mdpi.com

150. F. Liu, J. Qian, Y. Zhu, P. Wang, J. Hu, and B. Lu, "Phosphate solubilizing microorganisms increase soil phosphorus availability: a review," Geomicrobiology, 2024. [HTML]

151. R. Sarmah and A. K. Sarma, "Phosphate solubilizing microorganisms: A review," *Communications in Soil Science and Plant Analysis*, vol. 2023, Taylor & Francis. [HTML]

152. Z. Ahmed, "The Interplay of Food Development, Nutrition and Sensory Evaluation: A Comprehensive Review," researchgate.net, . researchgate.net

153. N. T. P. Sari and E. Yulianto, "A Literature Review: Unraveling the Dimensions of Food Quality and Its Influence on Consumer Satisfaction," KnE Social Sciences, 2024. knepublishing.com

154. N. K. M. Prachi, "Selection and performance of sensory panelists: A comprehensive review of factors influencing sensory evaluation outcomes," J. Nutrition and Food Processing, 2024. researchgate.net

155. T. T. Alemu, P. Intipunya, and B. A. Gebeyo, "A comprehensive review of edible coatings for postharvest management of fruits and vegetables: enhancing food and nutrition security," Discover Agriculture, 2025. springer.com

156. B. Lohita and M. Srijaya, "Novel Technologies for Shelf-Life Extension of Food Products as a Competitive Advantage: A Review," Food production, diversity, and safety under climate …,

2024. [HTML]

157. L. Nian, M. Wang, X. Sun, Y. Zeng, and Y. Xie, "Biodegradable active packaging: Components, preparation, and applications in the preservation of postharvest perishable fruits and vegetables," *Reviews in Food Science and Nutrition*, vol. 2024, Taylor & Francis. [HTML]

158. S. Panwar, K. S. Duggirala, P. Yadav, and others, "Advanced diagnostic methods for identification of bacterial foodborne pathogens: Contemporary and upcoming challenges," Critical Reviews in ..., vol. 2023, Taylor & Francis. [HTML]

159. L. Singh and V. S. Sharanagat, "Application of biosensors against food-borne pathogens," Nutrition & Food Science, 2024. emerald.com

160. Y. Feng, J. Shi, J. Liu, Z. Yuan et al., "Advancing food safety surveillance: rapid and sensitive biosensing technologies for foodborne pathogenic bacteria," Foods, 2025. mdpi.com

161. A. Gatto and M. Chepeliev, "Global food loss and waste estimates show increasing nutritional and environmental pressures," Nature Food, 2024. wur.nl

162. S. Vesković Moračanin, M. Milijašević, "Food loss and waste: a global problem," Meat Technology, 2023. nivs.rs

163. MD Junaid and AF Gokce, "Global agricultural losses and their causes," Bulletin of Biological and Allied Sciences, 2024. bbasr.org

164. R. Lahlali, S. Ezrari, N. Radouane, J. Kenfaoui, et al., "Biological control of plant pathogens: A global perspective," Microorganisms, vol. 10, no. 7, 2022. mdpi.com

165. Z. Wang, Y. Sui, J. Li, X. Tian, and Q. Wang, "Biological control of postharvest fungal decays in citrus: a review," *Critical Reviews in Food Science and Nutrition*, vol. 62, no. 1, pp. 1-15, 2022. [HTML]

166. N. Ninama, L. Gangal, A. Khayum, H. S. B., "Post-harvest biotechnology or genetic engineering solutions: Extending shelf

life and reducing food waste," in *Biotechnology*, 2024. researchgate.net

167. J. Huang, M. Zhang, A. S. Mujumdar, "Technological innovations enhance postharvest fresh food resilience from a supply chain perspective," Critical Reviews in Food Science and Nutrition, 2024. [HTML]

168. K. Mounika, P. P. Reddy, R. P. Singh, and A. Pandey, "Post-harvest TECHNOLOGIES and cold chain management: A review," Plant..., 2025. researchgate.net

169. T. C. Ogedengbe, O. J. Malomo, and N. E. Akanji, "Post-harvest losses and reduction techniques in crop production: a review.," 2022. [HTML]

170. M. Venbrux, S. Crauwels, and H. Rediers, "Current and emerging trends in techniques for plant pathogen detection," Frontiers in Plant Science, 2023. frontiersin.org

171. M. Aladhadh, "A review of modern methods for the detection of foodborne pathogens," Microorganisms, 2023. mdpi.com

172. S. MacAulay, A. R. Ellison, P. Kille, "Moving towards improved surveillance and earlier diagnosis of aquatic pathogens: From traditional methods to emerging technologies," *Reviews in...,* vol. 2022, Wiley Online Library. wiley.com

173. A. Hassan, M. K. I. Khan, S. Fordos, A. Hasan, "Emerging foodborne pathogens: challenges and strategies for ensuring food safety," *Biology and Life*, vol. 2023, 2023. mdpi.com

174. M. Pattabhiramaiah et al., "Foodborne pathogens and food safety regulations," *Food Microbial and…*, 2023. [HTML]

175. M. Crotta, B. C. Prakashbabu, H. Holt, B. Swift, V. C. Pedada, "Microbiological risk ranking of foodborne pathogens and food products in scarce-data settings," Food Control, vol. 2022, Elsevier. sciencedirect.com

176. Y. J. Moon, S. Y. Lee, and S. W. Oh, "A review of isothermal amplification methods and food-origin inhibitors against detecting food-borne pathogens," Foods, 2022. mdpi.com

177. M. Zhang, J. Wu, Z. Shi, A. Cao, W. Fang, D. Yan, and Q. Wang, "Molecular methods for identification and quantification of foodborne pathogens," Molecules, vol. 27, no. 12, 2022. mdpi.com

178. M. P. Kabiraz, P. R. Majumdar, M. M. C. Mahmud, and S. Bhowmik, "Conventional and advanced detection techniques of foodborne pathogens: A comprehensive review," Heliyon, vol. 9, no. 3, 2023. cell.com

179. K. Wang, X. Lin, M. Zhang, Y. Li et al., "Review of electrochemical biosensors for food safety detection," Biosensors, 2022. mdpi.com

180. Z. Kakimova and D. Orynbekov, "Advancements in nano bio sensors for food quality and safety assurance-a review," *Journal of Food*, 2023. [HTML]

181. R. Szelenberger, N. Cichoń, W. Zajaczkowski, and M. Bijak, "Application of Biosensors for the Detection of Mycotoxins for the Improvement of Food Safety," Toxins, 2024. mdpi.com

182. S. Nath, "Advancements in food quality monitoring: integrating biosensors for precision detection," Sustainable Food Technology, 2024. rsc.org

183. V. Marozzo, A. Vargas-Sánchez, T. Abbate, "Investigating the importance of product traceability in the relationship between product authenticity and consumer willingness to pay," Sinergie Italian Journal of ..., vol. 2022. sijm.it

184. E.I. Vazquez Melendez and P. Bergey, "Blockchain technology for supply chain provenance: increasing supply chain efficiency and consumer trust," Supply Chain Management, 2024. emerald.com

185. G. Castellini, L. Lucini, G. Rocchetti, J. M. Lorenzo, "Determinants of consumer acceptance of new technologies used to trace and certify sustainable food products: a mini-review on blockchain technology," *Current Opinion in …*, vol. 2022, Elsevier. [HTML]

186. C. C. Obijianya, E. Yakamercan, M. Karimi, and S. Veluru, "Agricultural irrigation using treated wastewater: Challenges and

opportunities," Water, 2025. mdpi.com

187. H. Gökçek, Y. Kassem, and H. Seman, "Review on waste water reuse for irrigation towards achieving environmental sustainability," *International Journal of …*, 2023. ijeap.org

188. A. Christou, V. G. Beretsou, I. C. Iakovides, "Sustainable wastewater reuse for agriculture," *Nature Reviews Earth & Sustainability*, 2024. hal.science

189. A. Y. Stepanova, E. A. Gladkov, E. S. Osipova, O. V. Gladkova, "Bioremediation of soil from petroleum contamination," Processes, vol. 2022. mdpi.com

190. A. Malik and V. K. Garg, "Bioremediation for sustainable environmental cleanup," 2024. [HTML]

191. I. Kisić, J. Hrenović, Ž Zgorelec, G. Durn et al., "Bioremediation of agriculture soil contaminated by organic pollutants," Energies, 2022. mdpi.com

192. S. Madhav, R. Mishra, A. Kumari, A. L. Srivastav, "A review on sources identification of heavy metals in soil and remediation measures by phytoremediation-induced methods," *International Journal of …*, 2024. researchgate.net

193. W. Cui, X. Li, W. Duan, M. Xie, and X. Dong, "Heavy metal stabilization remediation in polluted soils with stabilizing materials: a review," *Environmental Geochemistry and Health*, vol. 2023, Springer. [HTML]

194. J. K. Sharma, N. Kumar, N. P. Singh, "Phytoremediation technologies and their mechanism for removal of heavy metal from contaminated soil: An approach for a sustainable environment," Frontiers in Plant Science, 2023. frontiersin.org

195. A. Mizyed, "A strategic framework for reusing partially treated wastewater in agriculture: Viability and sustainability prospects," Agricultural Water Management, 2025. sciencedirect.com

196. M. H. Tawfik, H. Al-Zawaidah, J. Hoogesteger, and M. Al-Zu'bi, "Shifting waters: the challenges of transitioning from freshwater to treated wastewater irrigation in the northern Jordan Valley," Water,

vol. 2023. mdpi.com

197. A. Jan, T. Ali, S. Chirag, S. Ahmed, M. Ali, S. Wali, "Eco-friendly management of insect pests and plant diseases using botanical extracts," *Research Journal of …*, 2026. grjnst.net

198. D. D. Manoharmayum, "Eco-Friendly Approaches to Disease Management in Horticulture: Integrating Biological Control and Organic Practices," Journal of Neonatal, 2025. researchgate.net

199. M. Ahmed, M. Asim, S. Ahmad, and M. Aslam, "Climate change, agricultural productivity, and food security," in *Global Agricultural Production*, 2023, Springer. researchgate.net

200. B. Gwambene, E. Liwenga, and C. Mung'ong'o, "Climate change and variability impacts on agricultural production and food security for the smallholder farmers in Rungwe, Tanzania," Environmental Management, 2023. [HTML]

201. S. K. Balasundram, R. R. Shamshiri, S. Sridhara, and N. Rizan, "The role of digital agriculture in mitigating climate change and ensuring food security: an overview," Sustainability, 2023. mdpi.com

202. V. Owino, C. Kumwenda, B. Ekesa, M. E. Parker, "The impact of climate change on food systems, diet quality, nutrition, and health outcomes: A narrative review," in Climate, 2022. frontiersin.org

203. I. J. Mirón, C. Linares, and J. Díaz, "The influence of climate change on food production and food safety," Environmental Research, 2023. [HTML]

204. X. Yuan, S. Li, J. Chen, H. Yu, T. Yang, C. Wang, and S. Huang, "Impacts of global climate change on agricultural production: a comprehensive review," Agronomy, 2024. mdpi.com

205. U. Hafeez, M. Ali, S. M. Hassan, M. A. Akram, "Advances in breeding and engineering climate-resilient crops: a comprehensive review," *International Journal of …*, 2023. researchgate.net

206. R. M. Rivero, R. Mittler, E. Blumwald, et al., "Developing climate- resilient crops: improving plant tolerance to stress combination," *The Plant*, vol. 2022, Wiley Online Library.

wiley.com

207. D. Thingujam, S. Gouli, S. P. Cooray, and K. B. Chandran, "Climate-resilient crops: Integrating AI, multi-omics, and advanced phenotyping to address global agricultural and societal challenges," Plants, 2025. mdpi.com

208. AS Toromade, DA Soyombo, E Kupa, "Reviewing the impact of climate change on global food security: Challenges and solutions," *International Journal of …*, 2024. researchgate.net

209. A. Saleem, S. Anwar, T. Nawaz, S. Fahad, and S. Saud, "Securing a sustainable future: the climate change threat to agriculture, food security, and sustainable development goals," Journal of Umm Al-Qura, 2025. springer.com

210. D. Neupane, P. Adhikari, D. Bhattarai, B. Rana, Z. Ahmed, "Does climate change affect the yield of the top three cereals and food security in the world?" Earth, vol. 2022. mdpi.com

211. R. Biswas, M. Alam, A. Sarkar, M. I. Haque, M. M. Hasan, "Application of nanotechnology in food: processing, preservation, packaging and safety assessment," Heliyon, 2022. cell.com

212. F. Donkor, M. N. Okafor, and J. O. Enyejo, "Investigating nanotechnology-based smart packaging for extending dairy product shelf life and improving food quality assurance," *International Journal of …*, 2025. researchgate.net

213. M. S. de Sousa, A. E. Schlogl, F. R. Estanislau, and V. G. L. Souza, "Nanotechnology in packaging for food industry: Past, present, and future," Coatings, 2023. mdpi.com

214. J. D. Valle-García, A. Ali, J. K. Patra, R. G. Kerry, "Integration of eco-friendly biological and nanotechnological strategies for better agriculture: a sustainable approach," in *Nanotechnology: Novel Approaches*, 2023, Springer. [HTML]

215. S. R. Balusamy, A. S. Joshi, H. Perumalsamy, "Advancing sustainable agriculture: a critical review of smart and eco-friendly nanomaterial applications," Journal of …, 2023. springer.com

216. D. Maity, U. Gupta, and S. Saha, "Biosynthesized metal oxide

nanoparticles for sustainable agriculture: next-generation nanotechnology for crop production, protection and management," Nanoscale, 2022. academia.edu

217. S. Ali, N. Ahmad, M. A. Dar, S. Manan, and A. Rani, "Nano-agrochemicals as substitutes for pesticides: prospects and risks," *Plants*, 2023. mdpi.com

218. Y. Tang, W. Zhao, G. Zhu, Z. Tan, L. Huang, and P. Zhang, "Nano-pesticides and fertilizers: Solutions for global food security," *Nanomaterials*, vol. 13, no. 4, 2023. mdpi.com

219. D. Abdollahdokht, Y. Gao, S. Faramarz, et al., "Conventional agrochemicals towards nano-biopesticides: an overview on recent advances," *Chemical and Biological Engineering Reviews*, vol. 2022, Springer. springer.com

220. R. Sivakumar and N. Y. Lee, "Recent advances in airborne pathogen detection using optical and electrochemical biosensors," Analytica chimica acta, 2022. nih.gov

221. C. Y. Hsu, R. O. Saleh, H. Pallathadka, A. Kumar, "Advances in electrochemical-optical dual-mode biosensors for detection of environmental pathogens," *Analytical Chemistry*, 2024. academia.edu

222. M. Banakar, M. Hamidi, Z. Khurshid, M. S. Zafar, and J. Sapkota, "Electrochemical biosensors for pathogen detection: an updated review," *Biosensors*, 2022. mdpi.com

223. T. Mkhari, J. O. Adeyemi, and O. A. Fawole, "Recent advances in the fabrication of intelligent packaging for food preservation: a review," Processes, 2025. mdpi.com

224. E. K. Radhakrishnan, A. Jose, and S. Pareek, "Postharvest nanotechnology for fresh horticultural produce: Innovations and applications," 2023. [HTML]

225. R. S. Alibekov, K. U. Urazbayeva, A. M. Azimov, A. S. Rozman, "Advances in biodegradable food packaging using wheat-based materials: fabrications and innovations, applications, potentials, and challenges," *Foods*, 2024. mdpi.com

226. B. Suldovsky and H. Akin, "The role of trust in communicating scientific consensus and the environmental benefits of genetically engineered crops: Experimental evidence of a backfire effect," Environmental Communication, 2023. [HTML]

227. S. A. Siddiqui, Z. Asif, M. Murid, I. Fernando, and D. N. Adli, "Consumer social and psychological factors influencing the use of genetically modified foods—a review," *Sustainability*, vol. 2022. mdpi.com

228. V. Yadav, D. Pal, and A. K. Poonia, "A study on genetically engineered foods: need, benefits, risk, and current knowledge," Cell Biochemistry and Biophysics, 2024. [HTML]

229. R. Sendhil, J. Nyika, S. Yadav, J. Mackolil, "Genetically modified foods: bibliometric analysis on consumer perception and preference," *GM Crops & Food*, vol. 2022. nih.gov

230. N. Rustamova, S. Inoyatova, D. Madazizova, "Genetically modified ecosystems: Innovative approaches in agriculture and their environmental impact," BIO Web of Conferences, 2024. bio-conferences.org

231. N. G. Mueller and A. Flachs, "Domestication, crop breeding, and genetic modification are fundamentally different processes: Implications for seed sovereignty and agrobiodiversity," Agriculture and Human Values, 2022. researchgate.net

232. S. Kjeldaas, T. Dassler, T. Antonsen, and O. G. Wikmark, "With great power comes great responsibility: why 'safe enough' is not good enough in debates on new gene technologies," Agriculture and Human Values, vol. 2023, Springer. springer.com

233. T. Varzakas and M. Antoniadou, "A holistic approach for ethics and sustainability in the food chain: the gateway to oral and systemic health," Foods, 2024. mdpi.com

234. S. A. O. Adeyeye, T. J. Ashaolu, and O. T. Bolaji, "Africa and the Nexus of poverty, malnutrition and diseases," *Critical Reviews in …*, 2023. Taylor & Francis. [HTML]

235. AD Nugroho, JP Cubillos Tovar, ST Bopushev, "Effects of

corruption control on the number of undernourished people in developing countries," Foods, vol. 2022. mdpi.com

236. A. Kiran, A. Wakeel, K. Mahmood, R. Mubaraka, and Hafsa, "Biofortification of staple crops to alleviate human malnutrition: contributions and potential in developing countries," Agronomy, 2022. mdpi.com

237. N. Pandey and H. de Coninck, "Beyond technology transfer: Innovation cooperation to advance sustainable development in developing countries," *Energy Reviews*, vol. 2022, Wiley Online Library. wiley.com

238. L. Craiut, C. Bungau, T. Bungau, C. Grava, P. Otrisal, "Technology transfer, sustainability, and development, worldwide and in Romania," Sustainability, vol. 2022. mdpi.com

239. E. M. da Fonseca, K. C. Shadlen, and H. de Moraes Achcar, "Vaccine technology transfer in a global health crisis: Actors, capabilities, and institutions," Research Policy, 2023. sciencedirect.com

240. V. D. Rajput, A. Singh, K. Ghazaryan, "Nanotechnology and biotechnology: transforming agriculture for food security and sustainability," in *Nanotechnology*, 2024. [HTML]

241. S. A. Atanda, R. O. Shaibu, and F. O. Agunbiade, "Nanoparticles in agriculture: balancing food security and environmental sustainability," Discover Agriculture, 2025. springer.com

242. F. Khan, P. Pandey, and T. K. Upadhyay, "Applications of nanotechnology-based agrochemicals in food security and sustainable agriculture: an overview," Agriculture, 2022. mdpi.com