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ROLE OF MODERN BIOTECHNOLOGY IN IMPROVING CROP PROTECTION

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Abstract *Biotechnology plays a transformative role in enhancing agricultural productivity and crop protection by integrating cutting-edge genetic tools, including genetic engineering, marker-assisted selection, and molecular diagnostics. These have led to the development of genetically modified crops (GMOs) and improved pest, disease, and abiotic stress resistance through gene editing techniques like CRISPR-Cas9. Besides that, innovations in bioinformatics and simulation modeling have optimized farming techniques, including residual harvesting, without causing detrimental environmental impacts like the emission of greenhouse gases and soil degradation. Residual harvesting has shown significant impacts on crop yield and soil health. Research shows that with accurate residue management, it is possible to enhance the fertility of the soil and the performance of crops while reducing carbon emissions and soil erosion. Molecular markers, such as SNPs and AFLPs, are instrumental in fast-tracking the breeding programs to produce varieties that are tolerant of biotic and abiotic stresses so that resilient crop varieties may be produced. Biotechnology applications, such as precision breeding, have transformed agriculture by introducing traits that include drought and heat tolerance, nutrient efficiency, and enhanced yields. Successful case studies, such as Bt cotton, golden rice, and blight-resistant potatoes, are illustrative of the potential biotechnology has to solve challenges in global food security. The IPM strategies, grounded in biotechnological breakthroughs, have reduced the usage of chemical inputs, therefore promoting sustainable farming practices. This multidimensional approach underscores biotechnology's role in addressing the challenges of a growing global population, ensuring food security, and fostering sustainable agricultural development. Through the merging of traditional practices with modern genetic tools, biotechnology presents a pathway toward resilient, high-yielding, and environmentally sustainable agricultural systems.*

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Introduction

Function of Biotechnology in improving Crop protection

Biotechnology has revolutionized agricultural practices using offering modern solutions to shield vegetation from pests, sicknesses, and environmental stresses. Through integrating modern-day genetic equipment, together with genetic engineering, gene editing, molecular diagnostics, and biotechnology allows the improvement of resistant crop sorts and sustainable farming practices. Techniques like the transgenic era have brought genes for resistance to pathogens, herbicides, and insect pests, considerably reducing reliance on chemical inputs and enhancing yield stability. Moreover, advancements in bioinformatics and molecular markers facilitate precision breeding for stress tolerance, as a multidimensional method (Anand, 2017).

Residual Harvesting: Insights and Impacts on Crop Yield and Soil Systems

There are many uses for residual harvesting, but data on the percentage of areas where this practice is limited. In the United States, research by (Bhatia et al., 2015) used data from the 2010 U.S. Corn Growers Agricultural Resource Management Survey to estimate harvesting costs. The results showed that most of the crops had not yet been harvested in 2010. The volume had increased significantly. In addition, higher yields, especially of corn, have encouraged stubble harvesting as an alternative to more intensive farming to accelerate crop yields. The impact on soil systems is significant. This understanding is important because crop yields and residual yields vary greatly depending on location and conditions. While simulation models can predict these changes, they must be calibrated and validated using locally collected data to ensure accuracy (Bhatia et al., 2015).

Assessing Crop Residue Harvesting and Simulation Modeling

Crops are harvested for many purposes, but data on the areas covered by this practice are limited. In the United States, analyzed data from the 2010 U.S. Corn Growers Agricultural Resource Management Survey to estimate straw harvest. The results showed that most of the crops had not yet been harvested in 2010. Increase residue collection. Additionally, increased yields of crops, especially corn, have encouraged the replacement of the remaining crops with heavy tillage to address crop problems (Bhattacharjee et al., 2024). Understanding the influence of soil is important to assess the potential impact of harvesting. This is important because crop yields and residue yields vary depending on location and environment. Simulation models can provide estimates of crop yields and residue yields, but they need to be validated using local data to ensure accuracy. Carbon flux tower data provide such evidence. For example, Zhan *et al*. (2019) used these data to validate their model in Nebraska and concluded that: (i) excess CO_2 emissions can be eliminated, (ii) the model is a good tool for generating a carbon budget, (iii) Crops can reduce CO_2 emissions (Bhattacharjee et al., 2024).

Effects of Residue Removal on Soil and Plant Health

Crop cleaning affects water and the cycle, which has negative consequences for crop production. Overharvesting can cause erosion, and soil crusting, reduce water infiltration, exacerbate water stress, ultimately reduce nutrient efficiency, and exacerbate insect problems (Clasen et al., 2016). Crops are growing, productive, and beautiful. In China, (Éva et al., 2018) found that returning crushed residue to the field increased the dry weight of corn by 18.5% and yield by 15.1%. Similarly, (Éva et al., 2018) found that grain yield increased and starch content changed in the hind. However, in some cases, as in maize and rice, residue removal is associated with decreased yield (Guo et al., 2023). He reported that short-term straw removal in Brazil reduced carbon emissions without affecting sugar production, while others found no decrease in maize, soybeans, or dry beans. In comparison (Guo et al., 2023),

Effects of Agricultural Practices on Carbon Storage and Greenhouse Gas Emissions

Changes in crop production and crop diversity can affect greenhouse gas (GHG) emissions, but proper testing requires an appropriate sample size to measure emissions. For example, (McCarty et al., 2020) found that in Kansas, the highest nitrous oxide (N2O) emissions occurred after a warm, short-duration rain event, with September accounting for 30–50% of recorded annual emissions (Hahn et al., 2020).

Genetic Engineering in Crop Breeding

Genetic engineering has revolutionized agriculture by altering genomes to improve productivity, stress, and nutritional quality. By adding, removing, or modifying specific genes, crops can be modified to exhibit traits that improve their performance in different environments, leading to food security and permaculture (Kang, 2024).

Development of Genetically Modified Crops (GMOs)

The development of genetically modified plants (GMOs) involves the addition of beneficial genes from other organisms or genetic modification to achieve the desired production. These methods often use technologies such as CRISPR-Cas9, Agrobacterium-mediated transformation, or particle bombardment (Lassoued et al., 2019). Genetically modified crops have been developed to address agricultural problems such as pest and disease resistance, antibiotics, and abiotic resistance. For example, crops modified with Bt soybeans using *Bacillus thuringiensis* can produce proteins that are toxic to certain pests, thereby reducing the need for pesticides. Crops undergo rigorous safety checks before they are released to ensure they are safe for the environment and human health (Lassoued et al., 2019).

Traits Engineered for Improved Crop Yield and Quality

Crop importance includes increased yield potential, improved nutrient utilization, and resistance to biotic and abiotic stresses. Genes controlling photosynthesis, nutrition, and growth hormones are being modified to increase yield. Healthcare includes supplementing rice and other crops with essential vitamins; for example, golden rice is rich in provitamin A, which can prevent vitamin A deficiency. Disease-resistant crops such as papaya and potato have also been developed. The addition of genes controlling water retention, osmotic balance, or stress can provide tolerance to stresses such as drought, salt, and heat, allowing crops to adapt to climate change (Macedo et al., 2015).

Case Studies of Successful Genetically Modified Crops

Many genetically modified crops have been shown to benefit agriculture and society. Bt cotton is one of the first commercially successful ways to transform diseases, reduce pesticide use, and increase profits for millions of farmers worldwide. Golden rice with added provitamin A could address micronutrient deficiencies in regions. Herbiside-modified soybeans and corn facilitate weed control, enable conservation tillage practices, and improve soil health. Antiviral papaya protects Hawaiian commercial papaya from papaya ringspot virus. Recently, genetically modified potatoes resistant to late blight have shown promise in reducing reliance on fungicides. These examples show how genetically modified organisms can solve specific problems, increase crop productivity, and contribute to global food security while reducing agricultural costs (McCarty et al., 2020).

Molecular Markers and Marker-Assisted Selection

The use of molecular genetic markers in plant breeding has grown significantly, with marker-assisted selection (MAS) being recognized as a valuable tool to enhance selection efficiency. While organic agriculture does not explicitly exclude molecular markers, their appropriateness is often debated due to organic farming principles that reject genetically modified organisms (GMOs) and focus on health, ecology, care, and fairness (McCarty et al., 2020). Concerns about GMOs in organic farming center on perceived health and environmental risks, the socio-economic dominance of multinational corporations, and the reductionist approach to life inherent in GMO technologies (Osendarp et al., 2021). Although molecular markers are diagnostic tools that do not directly alter the genome, their compatibility with organic breeding programs is questioned. Challenges include the limited availability of markers for complex traits like nutrient efficiency and weed suppression, which are critical for organic farming. As a result, field-based phenotypic selection remains the preferred method. Additionally, protocols for molecular markers often involve chemicals or enzymes derived from GMOs, which are prohibited under US and EU organic regulations. This limitation underscores the need for alternative approaches in breeding for organic agriculture (Osendarp et al., 2021).

Role of Molecular marker in Plant breeding

Advances in genetics, molecular biology, and biotechnology are enabling breeders to produce new crops with high yields. The introduction of DNA markers, particularly those using the polymerase chain reaction (PCR), has revolutionized the study of genetics. Molecular markers mark specific genes and help determine their location relative to other genes, making them targets for further research (Paril et al., 2024). Hybridization-based markers include restriction fragment length polymorphism (RFLP), while PCR-based methods have increasingly more reliable polymorphic markers (Table 1). These include amplified fragment length polymorphism (AFLP), random amplified polymorphic DNA (RAPD), Amplified sequence repeat (ISSR), and single nucleotide polymorphism (SNP), which represent genetic analyses and grow in cultivation (Paril et al., 2024).

Table 1: Types of Marker

Types of Marker	Description	Applications	Ref
Molecular markers	Use DNA-based techniques to detect genetic variation. Examples include RAPD, SSR, SNP, and AFLP markers.	Used in marker-assisted breeding, genetic mapping, and gene tagging.	(Parmar et al., 2017)
RAPD (Random Amplified Polymorphic DNA)	Uses random primers to amplify DNA regions; which useful in detecting genetic diversity.	Identification of genetic variability and genetic mapping in plants.	(Xiong et al., 2021)
AFLP (Amplified Fragment Length Polymorphism)	Combines restriction enzyme digestion with PCR amplification to generate DNA markers; reveals polymorphisms in DNA sequence.	Used in genetic diversity studies, marker-assisted selection, and linkage mapping.	(Shimatani et al., 2017)
SSR (Single sequence repeats)	Also known as microsatellites, these are regions of repeated DNA sequences; highly polymorphic.	Applied in breeding programs, genomic selection, and disease resistance studies.	(Singh et al., 2015)
SNP (Single Nucleotide Polymorphism)	Detects variations at a single nucleotide position in the genome; high-throughput techniques allow efficient detection.	- Disease resistance gene identification - Crop improvement	(Kang, 2024)
ISSR (Inter-Simple Sequence Repeat)	Uses primers that amplify regions between simple sequence repeats.	- Genetic diversity studies - Phylogenetic analysis	(Bhatia et al., 2015)
QTL (Quantitative Trait Loci) Markers	Identifies genetic regions responsible for quantitative traits (e.g., yield, resistance).	- Identification of traits for selection - Crop improvement	(Clasen et al., 2016)
Dominant Markers	Markers that only detect one allele, are used for identifying the presence or absence of a trait.	Gene mapping - Selection of heterozygous individuals	(Macedo et al., 2015)
Transgenic Markers	Specific markers are used to identify and track transgenic events in genetically modified	- Gene introgression - Screening for trait presence	(Clasen et al., 2016)

	organisms.		
Codominant Markers	Markers that allow for the detection of both alleles in a heterozygous individual.	- GMO detection - Quality control in GM crops	(Clasen et al., 2016)

Enhancing Disease Resistance and Stress Tolerance

Molecular markers have revolutionized plant breeding by providing precise tools to identify and select desired traits at the genetic level. These markers, such as SSRs (simple sequence repeats), SNPs (single nucleotide polymorphisms), and AFLPs (long fragment length polymorphisms), work as a DNA interaction between traits such as disease resistance and stress in specific areas. By integrating these traits into breeding programs, researchers can facilitate the development of stronger, more productive crops (Parmar et al., 2017).

- **Disease-Specific Resistance:** Molecular markers can be linked to specific resistance genes, such as those that combat fungal diseases like late blight in potatoes or rust in wheat. By identifying these markers, breeders can introduce resistance traits into susceptible cultivars.
- **Durable Resistance:** MAS also aids in pyramiding multiple resistance genes into a single variety, providing long-term protection against evolving pathogens.
- **Early Detection and Screening:** Markers enable early identification of resistant seedlings, saving time and resources compared to conventional breeding (Permyakova and Deineko, 2024).

Improving Stress Tolerance

Abiotic stresses together with drought, salinity, and high temperature can pose serious issues in crop production, often resulting in low yields and affecting food protection. Molecular markers play an essential position in developing stress-tolerant vegetation using figuring out and mapping genetic loci associated with these developments (Permyakova and Deineko, 2024). For drought tolerance, deep-rooted and water-efficient seeds need to be favored, thus, types that can grow in less water ought to be preferred. Further, salt-tolerant plants may be bred by using concentrated alerts related to ion delivery and osmoregulation, so that plant life holds cell homeostasis in the absence of salt (Anwar et al., 2024). for heat and bloodless stress, pressure proteins and genes associated with the cold process can assist in growth the adaptation, and sustainability of crops that could face up to high temperatures to weather trade. This vital provider offers an excellent way to boost crop resistance to abiotic illnesses (Pucker et al., 2021).

Applications in Precision Breeding

Precision breeding combines molecular markers with technologies such as genome editing and genome selection to produce high-quality, accurate crops. This method allows breeders to produce crops that can be used for specific agricultural purposes. This method is particularly useful for creating complex traits that are influenced by many genes, such as stress stability. GS increases breeding accuracy by focusing on genetic information (Rajyaguru et al., 2024). For example, disease resistance and drought tolerance can be combined to allow plants to withstand multiple stresses simultaneously (Akram et al., 2023). Similarly, molecular markers speed up the breeding cycle through "fast breeding," allowing for rapid selection of desired traits and reducing the time required to produce new crops. Like CRISPR-Cas9, this approach allows for the modification of specific regions of the genome, providing precision while controlling variation. Together, these applications lead to a revolutionary concept in permaculture and crop improvement (Rajyaguru et al., 2024).

Role of Plant Protection for Improving Agricultural Production and Productivity

The growing global population, predicted to reach 10 billion by 2050, poses a primary task to meal production. To fulfill the growing call, new techniques are needed to increase agricultural productivity and stop starvation, which presently impacts more than a million humans globally. However, agricultural manufacturing faces many constraints, which include abiotic stresses (including drought, flooding, and warmth) and biotic factors, particularly pests (Römer et al., 2007). Plant safety, along with pest control, plays an critical position in reducing these issues and ensuring meals security. Biotechnology has come to be an important part of the sphere with the aid of improving pest detection, the know-how of pest sicknesses, and developing pest management strategies such as included pest control (IPM). Pests, consisting of insects, illnesses, and weeds, account for fifty% of agricultural losses. Powerful pest control the usage of a combination of culture, chemistry, biology, and genetics is vital to permaculture. By way of fixing pest troubles, plant protection can benefit agriculture, ensure food safety, and promote sustainable improvement (Römer et al., 2007).

Role of Biotechnology in Plant Protection and Agriculture

The role of biotechnology in plant protection and agriculture Biotechnology as defined by the Convention on Biological Diversity (CBD, 1992), is the use of living organisms, insects, or materials to replace or produce product machinery. Agricultural biotechnology includes many tools and techniques to control diseases or their products to improve plant protection and agricultural productivity. These technologies include DNA-based behavior, molecular breeding, recombinant DNA technology, bioprocess engineering, and bioinformatics, which together represent applications in biological research (Rozov et al., 2019)

Biotechnology in Plant Protection

The position of biotechnology in plant protection may be divided into businesses: (1) disease management and (2) pesticides. Advances within the first class can assist pick out plant markers and DNA areas for pests, allowing for rapid, accurate pest identity and genetic evaluation. This has accelerated the improvement of resistant types and progressed pest control techniques (Akram et al., 2024). On the subject of pest control, biotechnology includes each method and modern-day technologies together with molecular breeding and genetic engineering. Especially, today's technology is swiftly developing; imparting higher solutions for pest management. Numerous reviews discuss the use of biotechnology in controlling plant diseases, pests, and weeds and display its widespread impact on pest development **(**Schreiber et al., 2024).

Biotechnology for Improving Agricultural Production and Productivity

The development of agricultural technology has gone through two primary tiers: the "green revolution" (1944-1994) and the current "genetic revolution" that began in the mid-1990s. The Green Revolution depended on the use of agrochemicals, equipment, and high-yield plants evolved through breeding. While this method has helped growth productiveness, it has struggled to maintain pace with the international populace boom. The genetic amendment, or current biotechnology, emerged by breaking the bounds of conventional breeding by combining genetic engineering (Shimatani et al., 2017). Latest biotechnology combines genetic amendment with breeding, bioinformatics, molecular genetics, and numerous components of plant physiology to provide vegetation that is proof against biotic and abiotic strain elements. As a result, biotechnology has expanded agricultural manufacturing and food security by way of improving plants greater precise and rapid and by permitting the integration of favored developments into flora (Shimatani et al., 2017).

Biotechnology for Pest Management

Biotechnology in pest control can be broadly divided into biotechnological techniques and contemporary biotechnological methods. Conventional pest management includes non-genetic changes, while present-day biotechnology includes superior techniques consisting of molecular breeding and genetic engineering. Brand new generations could make pest control greater powerful and green via genetically modifying plants or pests. This assessment affords an overview of how biotechnology is used to control plant sicknesses, pests, and weeds, demonstrating the use of each strategy. These approach goals are to update preceding analyses, offer better information on the function of biotechnology in pest management, and make contributions to the development of permaculture practices (Singh et al., 2015).

Future Directions and Innovations in Crop Biotechnology

The future of crop biotechnology can revolutionize agriculture. As the sector's population keeps developing, the want for excessive-yield, excessive-yield, and weather-secure vegetation is growing. Innovations in biotechnology play a key role in fixing these problems, and destiny instructions in this region are likely to focus on a variety of technological innovations, together with new technology, the mixing of big statistics and synthetic intelligence (AI), and improved precision in agriculture. Those improvements require changes in crop management, optimizing productivity, and environmental sustainability (Subramanyam et al., 2011).

Emerging Technologies in Crop Management

New technologies in crop control are changing the rural landscape. This type of technology is gene editing, mainly CRISPR/Cas9, that could alternate genetic make-up. This results in the improvement of better vegetation, along with those that can be immune to diseases, pests, and environmental strain. Moreover, superior breeding techniques, together with molecular breeding and artificial biology are permitting plants to develop with blessings along with nutritional value and progressed fidelity (Subramanyam et al., 2011). This technology holds terrific promise in overcoming challenges posed using climate change, land degradation, and resource scarcity. As the arena actions to more sustainable power assets, biotechnology is supporting to development of plants that produce better biofuels, decreasing dependence on fossil fuels and lowering environmental impacts. Plant biotechnology is also supporting to development of vegetation that may be grown in bad soils or terrible environments, making them more tremendous in regions previously concept flawed for agriculture (Xiong et al., 2021).

The role of big data and AI in biotechnology

The integration of large records, artificial intelligence (AI), and biotechnology is converting the manner we control plants and plant life. Huge statistics can collect and examine facts from an expansion of assets, consisting of climate information, humidity, crop yields, and pests. Using statistics in this manner can assist researchers perceive styles and relationships that might otherwise be not noted, making crop management strategies greater effective and green (Yadav et al., 2024). It's used to expect plant increase, optimize water use, and detect early signs of sickness or pests. AI-powered equipment can also assist create predictive models that assist farmers make more knowledgeable decisions about crop-making plans, planting, and pesticides—all free, that may help increase crop yields and reduce environmental effects. The combination of big data and artificial intelligence is pushing the boundaries of crop biotechnology, offering new insights that can boost performance whilst reducing aid use (Zhao et al., 2019).

The Future of Precision Agriculture and Biotechnology

The destiny of precision agriculture and biotech vegetation is today. Biotechnology plays a key position in precision agriculture by way of supplying better vegetation for precise situations or farming. For instance, changed crops may be relied upon to lessen irrigation or increase resistance to pests, thereby growing productivity and decreasing resource waste (Anand, 2017). For instance, drone generation for immediate monitoring of vegetation, faraway sensing, and soil fitness. This integration will allow farmers to make extra decisions about when and how to observe fertilizer, insecticides, and water, making farming greater efficient and usable. Additionally, the use of plant boost-promoting microbial inoculants and microorganisms (PGPR) inside the rhizosphere will boost crop yields by way of improving soil fitness and nutrition which is essential for crop production internationally (Anand, 2017).

Conclusion

Biotechnology in Modern-day Crop Control Biotechnology has turned out to be an important device in present day crop control, offering answers to a number of the maximum challenging issues in agriculture. Biotechnology improves global meal protection through making flora-proof against illnesses, pests, and environmental stress via genetic engineering, molecular breeding, and superior generation. Improvements in crop biotechnology are also increasing the dietary fee, yield, and tolerance of vegetation to weather trade, and selling permaculture. The mixing of biotechnology with other emerging technologies, together with huge records, artificial intelligence, and precision agriculture, is increasing its effect and making it viable to increase crop yields whilst reducing resource use and environmental impact.

Future Challenges and Opportunities

Despite great advances in crop biotechnology, many demanding situations are continuing. One key issue is regulatory approval, as GMO plants face strict policies in lots of elements of the sector. Public knowledge of biotechnology remains a challenge due to issues approximately food safety and environmental influences. Solving those issues calls for obvious conversation, sizeable studies, and training to build belief and expertise among customers, policymakers, and communities. Biotechnology can produce crops that may resist intense climate situations, boost soil fertility, and gain higher yields with fewer inputs. The continuing integration of technology together with artificial intelligence and massive information into crop biotechnology will toughen agriculture and sustainability. With the aid of solving those problems and exploiting these possibilities, biotechnology can play a sizeable position within the future development of agriculture and assist a developing population whilst protecting the environment.

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Declarations

Conflict of Interest

The authors have declared no conflict of interest.

Declaration of Interest Statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work.

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Author's contributions

JA and NN wrote the initial draft of manuscript. MTM, QA, UAM, and TZ collected the literature and wrote the manuscript, and edited the manuscript in original. All authors have read and approved the final manuscript.

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Not applicable

Consent for Publication

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