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Adaptive resource-saving technologies in agriculture: the role of biotechnologies and their impact on environmental safety

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Abstract. The article examines the role of biotechnologies in agriculture and their impact on environmental safety. In the face of a growing population and changing climate conditions, it is important to develop adaptive technologies that promote resource conservation and reduce negative environmental impacts. Biotechnologies represent a powerful tool for creating such innovative solutions in agriculture. The article discusses various aspects of biotechnology application in agriculture, including increasing crop productivity, protecting plants from diseases and pests, and improving soil quality. Special attention is paid to environmental safety issues and comparative analysis of the impact of biotechnologies on the environment compared to traditional agricultural methods.

1 Introduction

The pursuit of meeting society's needs for food, feed, fiber, and biofuel while preserving environmental quality and economic viability has long been a goal of agriculture. With the world population projected to reach approximately 9 billion people in the next 30 years, the agricultural sector faces the challenge of meeting increased demand amidst climate change, limited arable land, and water resources. Without the development of crops that can outperform current varieties, agricultural expansion and increased inputs may be necessary, exacerbating environmental pressures. Achieving food security in this context requires an integrated and diversified approach.

Food security, defined as ensuring all people have access to sufficient, safe, and nutritious food for an active and healthy life, is influenced by various factors including agricultural productivity and environmental sustainability. Agricultural biotechnology, encompassing technologies that use biological systems to modify products or processes, offers great potential for sustainable agriculture and food security. Traditional breeding methods and modern genetic tools, including genetic modification (GM) techniques, contribute to crop improvement [1].

The adoption of GM crops has steadily increased, particularly in developing countries, with advancements focused on insect resistance, herbicide tolerance, and stacked traits

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offering multiple modes of action. Emerging biotechnology approaches aim to enhance yield, reduce inputs, and provide protection against pathogens and abiotic stresses. Life cycle assessment models are valuable for evaluating the benefits and potential impacts of agricultural biotechnology.

2 Research methodology

Sustainable agriculture is all about finding that delicate balance between meeting the needs of the present without compromising the ability of future generations to meet their own needs. It's about farming in a way that not only ensures food security but also protects our natural resources and supports the well-being of farmers and communities. By minimizing the use of synthetic inputs like chemical fertilizers and pesticides, sustainable agriculture aims to reduce environmental pollution and preserve soil health.

Agronomic markers: These markers are related to the performance of plants in agricultural settings, focusing on traits that impact yield, disease resistance, and tolerance to environmental stresses. Agronomic markers are used to evaluate the overall productivity and resilience of crops under different growing conditions. Examples of agronomic markers include traits such as plant height, flowering time, seed size, and root architecture. These markers help breeders select for desired traits and develop cultivars that perform well in specific environments.

Overall, the combination of these different types of markers provides valuable tools for researchers, breeders, and farmers to understand and improve agricultural systems for increased productivity, sustainability, and resilience [2].

3 Results and Discussions

Genomic selection (GS) is a cutting-edge breeding approach that leverages genomic data to predict the breeding values of individuals based on their genetic markers. Here's an overview of the general procedure involved in genomic selection:

1. Selection of a training population: The initial step in GS is to assemble a diverse yet representative training population that mirrors the genetic variation present in the target breeding population. This population should be large enough to ensure robust statistical power for model training.

2. Genotyping of the training population: Next, the individuals in the training population undergo genotyping using advanced technologies such as SNP arrays or whole-genome sequencing. This process generates extensive genetic data for each individual, capturing variations across the genome.

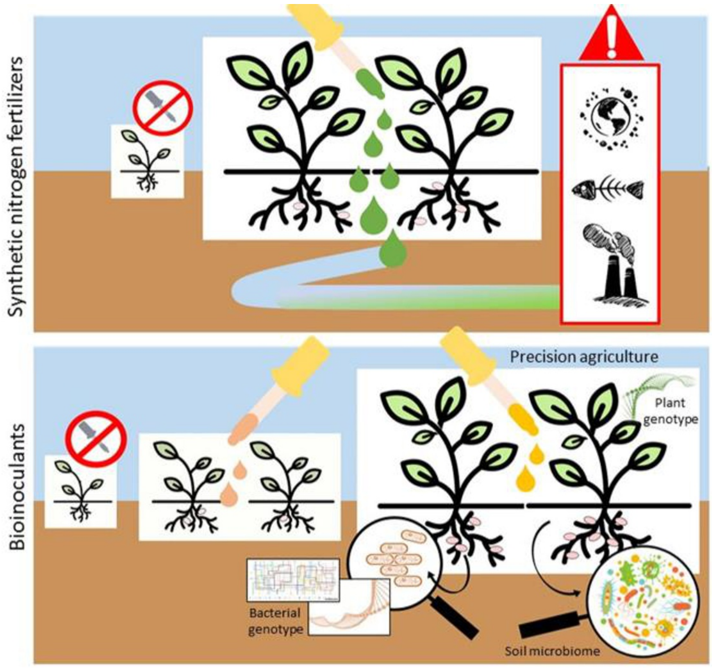

Fig. 1. Bioinoculants represent a sustainable complement to conventional practices

For instance, bioinoculants with the ability to fix atmospheric nitrogen can complement synthetic nitrogen fertilization and can represent a smart solution in light of precision agriculture, being present and more active in contact with the plant and when the plant needs more nitrogen. Moreover, specificity for plant genotypes and soil types allows to reduce the lab-to-the-field gap, increasing plant colonization and survival in the environment.

3. Phenotyping of the training population: The training population is then phenotyped for the traits of interest. Phenotypic data, alongside genotypic data, is crucial for training the statistical model to accurately predict breeding values.

4. Data preparation and quality control: Before analysis, the genotypic and phenotypic data undergo thorough preparation and quality control procedures. This involves removing low-quality samples, filtering out markers with low minor allele frequency, and ensuring markers are in Hardy-Weinberg equilibrium.

5. Statistical modeling [3]: The cleaned genotypic and phenotypic data are utilized to train a statistical model that establishes the relationship between genetic markers and phenotypic values. Various statistical approaches, such as ridge regression, Bayesian regression, and neural networks, can be employed for this purpose.

6. Cross-validation and model selection: The performance of the statistical model is evaluated using cross-validation techniques like k-fold cross-validation. This assessment helps identify the most accurate model for predicting breeding values.

7. Prediction of breeding values: The selected statistical model is then applied to predict the breeding values of new individuals based on their genetic markers. These predicted values serve as a guide for selecting individuals for breeding programs or prioritizing them for further phenotyping.

8. Validation and implementation [4]: The predictions generated by the selected model are validated in independent populations to assess their accuracy and robustness.

Subsequently, the best-performing model is integrated into the breeding program to enhance the desired traits effectively.

Genomic selection is becoming an increasingly important tool in plant breeding to develop improved varieties for farmers.

In summary, genomic selection offers a potent strategy for accelerating genetic improvement in crops and livestock. By integrating genomic data with advanced statistical techniques, GS enables more precise and efficient selection of individuals with desirable traits, ultimately leading to enhanced agricultural productivity and sustainability.

Diseases pose a significant threat to crop yield and can result in substantial losses in agricultural productivity. While the use of agrochemicals has traditionally been employed to manage diseases, it often leads to environmental hazards and the development of chemical-resistant pests[5]. To address this challenge, scientists have utilized transgenesis to breed plants with disease resistance traits, resulting in the development of genetically modified organisms (GMOs) with enhanced resistance to pathogens.

1. Disease Resistant Transgenic Crops:Through transgenesis, plants have been engineered to resist various diseases caused by viruses, fungi, and bacteria. For instance, transgenic papaya and squash have been developed to resist Papaya Ringspot Virus (PRSV), while transgenic bean and potato exhibit resistance against Bean Golden Mosaic Virus (BGMV) and potato late blight, respectively. The introduction of genes encoding viral coat proteins or viral replication inhibitors confers resistance to specific pathogens.

2. Nutritionally Improved Transgenic Crops: Transgenesis has also been utilized to enhance the nutritional qualities of crops [6]. Examples include Golden Rice, biofortified with increased levels of pro-vitamin A, and transgenic potato tubers expressing essential amino acids. Additionally, transgenic tomatoes with enhanced β-carotene content and maize with increased lysine production demonstrate the potential of biotechnology to address nutritional deficiencies.

3. Tissue Culture: Tissue culture techniques enable the propagation of plants under sterile conditions, allowing for the mass production of disease-free and genetically uniform plant material. Tissue culture has been instrumental in the propagation of banana varieties, such as Grand Naine (G9), and the production of disease-free plants through meristem tip culture. Moreover, tissue culture is utilized for the conservation of endangered germplasms and the maintenance of gene banks, especially for plants with recalcitrant seeds.

These biotechnological approaches highlight the versatility of transgenesis and tissue culture in addressing agricultural challenges, from disease management to nutritional enhancement and germplasm conservation [7]. As advancements in biotechnology continue, these techniques offer promising solutions for sustainable agriculture and food security.

Molecular Marker-Aided Genetic Analysis:This approach involves studying DNA sequences to identify genes, quantitative trait loci (QTL), and molecular markers associated with specific traits in organisms. Molecular marker-aided selection allows for the identification and tracking of DNA fragments across generations, facilitating the selection of desirable traits in breeding programs. For example, molecular markers have been used to identify rice genotypes resistant to diseases like Bacterial Blight and with desirable agronomic traits. Similarly, marker-assisted selection has aided in the identification of sources of disease resistance in coffee plants and the genetic analysis of traits like Fusarium Head Blight Resistance in wheat [8].

Doubled Haploid/Genome Doubling:Doubled haploids (DH) are genotypes formed when haploid cells undergo chromosome doubling, resulting in homozygous lines. DH technology accelerates the development of pure line varieties or inbred parental lines, reducing varietal development time. Techniques like anther-culture and chromosome elimination have been employed to produce DH plants in crops like wheat and rice, leading to faster genetic gains in yield and resistance.

Omics Technologies: Omics technologies, including genomics, proteomics, transcriptomics, genome sequencing, and metabolomics, provide comprehensive insights into the molecular composition and function of organisms. These approaches allow for the identification of genes, proteins, and metabolites associated with specific traits, aiding in crop improvement strategies. For instance, omics-based approaches have been used to develop herbicide-tolerant maize lines through precise gene insertion.

Concerns of Agriculture Biotechnology [9]: Despite the benefits, agriculture biotechnology raises concerns about ecological harm and food safety. Critics worry about the ecological impacts of gene manipulation in crops and the potential risks associated with consuming genetically modified organisms (GMOs). These concerns highlight the need for rigorous safety assessments and regulatory frameworks to ensure the responsible application of biotechnology in agriculture.

Genomics offers a plethora of opportunities to advance sustainable agriculture practices. Here's how genomics can contribute to promoting sustainability in agriculture:

1. Developing more resilient crops: Genomics enables the identification of genes associated with traits like pest resistance, disease resistance, and drought tolerance. By understanding these genetic factors, breeders can develop crop varieties that are better equipped to withstand environmental stresses. This reduces the need for pesticides and other chemical inputs while ensuring crop productivity.

2. Improving crop yields: Through genomics, researchers can unravel the genetic basis of important traits related to yield, quality, and nutrient uptake in crops. This knowledge allows breeders to develop high-yielding varieties that require fewer inputs such as fertilizers. By optimizing plant genetics, farmers can achieve higher yields with reduced environmental impact.

3. Enhancing food quality and safety: Genomics facilitates the identification of genes influencing nutritional content and safety in crops. Researchers can utilize genomics to develop crops with enhanced nutritional profiles, such as increased levels of essential nutrients or reduced levels of harmful compounds. This contributes to improving food quality and safety for consumers.

4. Developing new biotechnologies: Genomics serves as a foundation for developing innovative biotechnologies that promote sustainability in agriculture [10]. For instance, advancements in gene-editing techniques enabled by genomics can accelerate the breeding process, allowing for the development of new crop varieties with desired traits more efficiently. These biotechnologies offer opportunities to address agricultural challenges while minimizing environmental impact.

Overall, genomics has the potential to revolutionize agriculture by providing tools and insights to develop sustainable farming practices [11]. By leveraging genomic information, farmers can enhance crop resilience, optimize yields, improve food quality, and mitigate environmental impact. Embracing genomics in agriculture holds promise for feeding a growing global population while safeguarding natural resources for future generations.

4 Conclusions

In addressing the increasing food requirements of the world's population, traditional breeding approaches have been insufficient to meet the growing demand. To address this challenge, advancements in molecular markers, gene editing technologies, and crop sequencing have become crucial. Understanding crops at the genetic level allows for more targeted and efficient breeding strategies.

Molecular markers, such as single nucleotide polymorphisms (SNPs), allow researchers to identify and track specific genes or genomic regions associated with desirable traits. Gene editing technologies, like CRISPR-Cas9, enable precise modifications to crop genomes, facilitating the development of new varieties with desired traits.

Sequencing techniques have become more accessible and cost-effective, allowing for the comprehensive analysis of crop genomes. Genome-wide association mapping and association panels help identify genetic variations linked to important traits, aiding in breeding efforts.

The availability of reference genomes for many crops and the assembly of pan-genomics datasets enable researchers to explore genetic diversity within crop species and identify unique genes that may confer valuable traits.

Integration of genomics into agriculture has proven successful in developing new crop varieties with improved yield, quality, and resilience to environmental stresses. By harnessing genomic information, breeders can select and develop crops that are better suited to meet the challenges of a changing climate and growing population.

Additionally, genomics plays a crucial role in promoting sustainable agriculture practices by enabling the development of crops with enhanced nutrient profiles, disease resistance, and reduced environmental impact.

Overall, the integration of genomics into agriculture holds great promise for addressing global food security challenges and ensuring a sustainable food supply for future generations.

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