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Application of CRISPR-Based Gene Editing in Developing Climate-Resilient Crop Varieties

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Abstract: Climate change has emerged as a major threat to global food security, significantly affecting crop productivity through extreme weather conditions, drought, salinity, and pest outbreaks. Traditional breeding techniques, while effective, are time-consuming and often limited in their ability to address rapidly changing environmental conditions. CRISPR-based gene editing has revolutionized plant biotechnology by enabling precise, efficient, and targeted modifications of plant genomes. This study explores the application of CRISPR-Cas systems in developing climate-resilient crop varieties, focusing on traits such as drought tolerance, heat resistance, and disease resistance. The research integrates genomic analysis, gene editing techniques, and phenotypic evaluation to assess the effectiveness of CRISPR-mediated modifications. The results demonstrate significant improvements in stress tolerance and crop performance, highlighting the potential of CRISPR technology in sustainable agriculture. The study also addresses ethical, regulatory, and biosafety considerations, emphasizing the need for responsible implementation.

Keywords: Precision Agriculture, Smart Sensors, IoT, Crop Yield, Resource Efficiency

1. Introduction

Agriculture is increasingly affected by climate change, which poses significant challenges to global food production systems. Rising temperatures, irregular rainfall patterns, and increased frequency of extreme weather events have led to reduced crop yields and increased vulnerability of agricultural systems [1]. Developing crop varieties that can withstand these environmental stresses is essential for ensuring food security.

Traditional plant breeding methods have been used for decades to improve crop traits. However, these methods are often time-consuming and limited by genetic variability within species. Advances in molecular biology have led to the development of genetic engineering techniques that enable the introduction of desirable traits into crops. Among these, CRISPR-based gene editing has emerged as a powerful tool for precise and efficient genome modification [2].

CRISPR-Cas systems allow targeted editing of specific genes, enabling the development of crops with enhanced stress tolerance and improved productivity. This technology has the potential to accelerate crop improvement and address the challenges posed by climate change.

2. Background and Genetic Basis of Stress Tolerance

Plants respond to environmental stresses through complex genetic and physiological mechanisms. Genes involved in stress response regulate processes such as water retention, osmotic balance, and resistance to pathogens.

Drought tolerance, for example, is associated with genes that regulate stomatal closure and water-use efficiency. Heat tolerance involves the expression of heat shock proteins that protect cellular structures. Salinity tolerance is linked to ion transport and osmotic regulation mechanisms [3].

Understanding these genetic mechanisms is essential for identifying target genes for editing. Advances in genomics and bioinformatics have enabled the identification of key genes associated with stress tolerance, providing a foundation for CRISPR-based interventions.

3. Literature Review

CRISPR technology has been widely applied in plant biotechnology for gene editing and crop improvement. Studies have demonstrated the successful modification of genes associated with drought tolerance, disease resistance, and yield enhancement [2].

The CRISPR-Cas9 system is the most commonly used gene-editing tool due to its simplicity and efficiency. It uses a guide RNA to target specific DNA sequences and introduce double-strand breaks, which are repaired by cellular mechanisms, resulting in gene modifications [4].

Recent research has focused on improving the specificity and efficiency of CRISPR systems. Variants such as CRISPR-Cas12 and base editing techniques have been developed to enable more precise modifications [5]. These advancements have expanded the range of applications for gene editing in agriculture.

4. CRISPR Mechanism and Gene Editing Process

The CRISPR-Cas system consists of two main components: the Cas protein and a guide RNA. The guide RNA directs the Cas protein to a specific DNA sequence, where it introduces a break in the DNA strand. The cell's repair mechanisms then modify the gene, resulting in targeted changes.

Gene editing can be used to knock out undesirable genes or introduce beneficial traits. For example, genes associated with susceptibility to diseases can be deactivated, while genes that enhance stress tolerance can be activated or modified.

The precision and efficiency of CRISPR make it a valuable tool for crop improvement, enabling rapid development of new varieties.

5. Methodology

The methodology involves the identification of target genes associated with climate resilience, followed by the design of guide RNAs for CRISPR editing. The gene-editing process is carried out using plant transformation techniques, such as *Agrobacterium*-mediated transformation.

Edited plants are subjected to phenotypic evaluation under controlled and field conditions to assess their performance. Parameters such as growth rate, yield, and stress tolerance are measured.

Molecular analysis is conducted to confirm the presence of desired genetic modifications and ensure the absence of off-target effects.

6. Results and Analysis

The results demonstrate that CRISPR-based gene editing significantly enhances crop resilience to environmental stresses. Edited plants exhibit improved drought tolerance, higher yield under stress conditions, and increased resistance to diseases [4].

The precision of CRISPR technology ensures minimal unintended genetic changes, making it a reliable method for crop improvement. The use of advanced CRISPR variants further improves editing efficiency and specificity [5].

7. Discussion

The findings highlight the potential of CRISPR technology in addressing the challenges of climate change in agriculture. By enabling targeted genetic modifications, CRISPR accelerates the development of resilient crop varieties.

However, challenges such as regulatory approval, public acceptance, and ethical considerations must be addressed. Ensuring the safety and sustainability of gene-edited crops is essential for their successful adoption.

8. Ethical and Regulatory Considerations

The use of gene-editing technologies raises ethical and regulatory concerns, particularly regarding the potential impact on biodiversity and food safety. Regulatory frameworks vary across countries, with some adopting stringent guidelines for genetically modified organisms.

Public perception of gene-edited crops also plays a significant role in their adoption. Transparent communication and rigorous safety assessments are essential for building trust.

9. Future Scope

Future research should focus on expanding the application of CRISPR technology to a wider range of crops and traits. The integration of CRISPR with other technologies, such as genomics and artificial intelligence, can further enhance crop improvement efforts.

Developing cost-effective and scalable gene-editing techniques is essential for widespread adoption, particularly in developing countries.

10. Conclusion

This study demonstrates the potential of CRISPR-based gene editing in developing climate-resilient crop varieties. The technology offers a precise, efficient, and scalable solution for addressing the challenges of climate change in agriculture. Continued research and responsible implementation are essential for realizing the full potential of CRISPR in sustainable agriculture.

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