

CRISPR-Based Genome Editing in Agricultural Crops: A Review

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ABSTRACT

Agricultural biotechnology has been transformed by enabling exact and quick gene alteration of crops with CRISpen-based genome editing technology. Knowing how to change certain genes in plants might help to greatly enhance food quality, disease prevention, and agricultural output. This research aims to evaluate their possibilities as well as their difficulties and how CRISpen-Cas9 and other CRISpen-based technologies may be used to improve crops. Excellent for changing genes, CRISpen-Cas9 may target specific DNA regions in many different living beings, including plants. Using this approach, foods better equipped to resist biotic and abiotic stresses, have greater nutritional value, and produces more are being grown in agriculture. Creating crops resistant to problems brought on by climate change including drought, heat, and salt of soil is among the most hopeful uses. Using CRISpen-Cas9, basic meals have also become healthier by integrating extra proteins, vegetables, and minerals our systems need. Growing food that are resistant to pests and illnesses is also made feasible by Crispen technology. Consequently, farming is more ecologically friendly and chemical herbicides are not as much required. Although changing genomes in agriculture using CRISpen offers a lot of amazing potential, there are several issues as well. Still major factors influencing their lack of mainstream adoption include regulation issues and general concerns over the safety of genetically modified crops. Using CRISpen technology raises moral questions as well, particularly with relation to gene drive systems that may alter wild plant groupings' genomes in an irreversible manner. Also, problems with technology like changes that happen in the wrong places, how well gene editing works in some plant species, and the long-term effects on the environment of genetically modified foods need to be fixed. This review talks about the latest progress and plans for the future of using CRISPR to change the genomes of crops. The review also points out areas that need more study and development, especially when it comes to making CRISPR tools more useful and accurate and figuring out how to work with legal systems. Overall, CRISPR-based gene editing shows a lot of promise for changing the way farming is done and making sure there is a steady supply of food in the face of world problems.

Keywords: CRISPR-Cas9, Genome editing, Agricultural biotechnology, Crop improvement, Food security

How to cite this article: Hinge D, Jadhav AV, Sharma S, Bhise S, Bansal K., CRISPR-Based Genome Editing in Agricultural Crops: A Review. *Int J Drug Deliv Technol.* 2026;16(1s): 1161-1176 DOI: 10.25258/ijddt.16.1161-1176

Source of support: Nil.

Conflict of interest: None

INTRODUCTION

Rapid changes in biotechnology are driving great advancements in agriculture. Some of the toughest issues in food security, ecology, and climate change opposition have been resolved thanks to their actions. One of the most important technologies available nowadays is CRISpen-based genome editing as it can accurately, efficiently, and flexibly change the genetic material of organisms. Using CRISpen-Cas9 technology has made improving agricultural traits directly influencing food production including nutritional value, disease tolerance, and yield easier. With population increase all around and climate change lowering the profitability of farming, CRISpen-based gene editing

has enormous possibilities to meet needs for environmental sustainability and food security. Genome editing is the precise modification of an organism's DNA to acquire desired features by means of adding, deleting, or altering genetic content. In the past, growing plants meant crossing different types of plants and choosing the best features. This process was slow and could last for several generations. While CRISPR-Cas9, on the other hand, makes it very easy and quick to change specific genes in plants. From the immune system of bacteria, Cas9, a partner protein, and CRISpen (Clustered Regularly Interspaced Short Palindromic Repeats) are very useful for precisely cutting DNA at specified places. This allows researchers to add or

correct certain genetic variances. Unlike other techniques of editing the genome, such as recombinant DNA technology and mutagenesis, which often resulted in unintended genomic modifications, this degree of precision distinguishes CRISpen. In many different fields of agriculture, crops are being improved by means of genomic editing utilizing CRISpen. Among its most significant uses is producing crops more impervious to environmental stresses. Climate change will most likely have a major impact on food supply and quality as it will modify temperature, rainfall, and frequency of extreme events. Many times unable to endure these kinds of changes, conventional crops are less lucrative and more likely to get diseases and pests.

Researchers are developing crops better able to handle drought, heat, salt, and other natural conditions by introducing genes resistant to them using CRISpen. Especially in regions most impacted by climate change, CRISpen is a pretty useful tool in the fight against food poverty as it alters crops to raise their resistance to damage. Apart from improving stress tolerance, CRISpen technology is also being utilised to produce more nutritional meals, which is a very important method to help in the worldwide hunger reduction. Commonly lacking in basic meals such rice, wheat, and maize are essential vitamins and minerals [1]. Communities reliant on these crops for food hence suffer from severe shortages. Using CRISpen, scientists could insert specific genes adding zinc, iron, and provitamin A (beta-carotene). Increasing their nutritional value might help these meals to be much healthier. Often referred to as "biofortification," this method may help reduce hunger in developing countries without basic access to a variety of foods. Using CRISpen in agriculture also helps to create crops better equipped to fight diseases and pests.

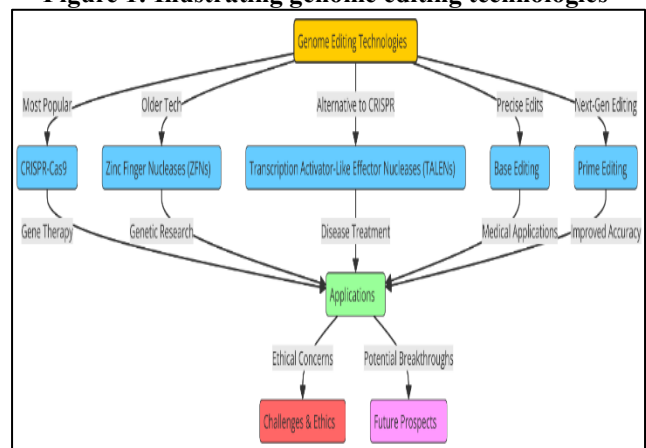
Although their increasing tolerance of pests and destruction of non-targeted species has generated environmental problems, pesticides and fungicides are regularly utilized to get rid of plant diseases. Crispen-based gene editing might be the answer as it lets us produce naturally resistance to certain pests crops, therefore lowering the need for pesticides. Scientists have successfully used CRISpen [2] to produce crops resistant to viruses, fungi, and bacteria that have been challenging to handle in the past. Although CRISpen technology has significant potential to transform agricultural methods, their usage in modifying crops is not always straightforward. These genetically modified crops may help to enhance surroundings, live longer, reduce unnecessary chemical treatments. Different nations regulate genetically altered organisms (GMOs) in somewhat different ways. While some nations have quite lax regulations for genetically modified crops, others have strong ones. Because genome editing does not necessarily include inserting foreign DNA, which are what genetically modified crops do [3], some people disagree on how to distinguish between them. This leads to demands for improved regulations considering the variations among these technologies while yet safeguarding consumers and the surroundings. The extent of use of CRISpen-based

meals also depends much on people's opinions about them. Although the technology has been hailed as a game-changer for sustainable farming, consumers are unsure if they should rely on it given concerns about the morality of altering genetic material and the unanticipated consequences of genetic alterations.

A. Background on genome editing technologies

Genome editing tools have come a long way in the last few decades, making it possible to precisely change an organism's genes. When recombinant DNA technology was first created in the 1970s, scientists were able to separate genetic material from different sources and put it back together again. Genomic editing had begun here. Later developments aimed at increasing the accuracy and applicability of these techniques for gene modification sought to Early techniques of genetic editing such as radiation and chemical mutagenesis did not choose which genes to alter. This made it difficult to locate the qualities sought for and required time [4]. Although recombinant DNA technology enabled the transfer of certain genes from one creature to another, it was not yet feasible to create modifications especially tailored to a given genomic location. Finding transcription activator-like effector nucleases (TALENs) and zinc-finger nucleases (ZFNs) marked the next major advance. These enzymes let scientists more easily target certain genes. For example, ZFNs depend on zinc finger proteins that can be made to bind to particular DNA regions. These proteins also have a nuclease domain that can break DNA double-stands at those locations. These technologies were a big step forward, but they were hard for many people to use because they were complicated and expensive. Newer inventions called TALENs also let you change specific parts of the genome by using proteins from bacteria, but they weren't as good at what they did or as easy to use

Figure 1: Illustrating genome editing technologies



With the creation of the CRISPR-Cas9 system in 2012, genome editing technology took a bigger step forward. Figure 1 is an outline of genome editing tools that shows how CRISPR, TALENs, and ZFNs work. This system completely changed genetic engineering. The CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) system was first found to protect bacteria against

viruses. It was then modified to work in human cells. With the help of a short RNA sequence, the Cas9 protein can be directed to a certain spot in the genome, where it makes a double-strand break. The cell's natural DNA healing systems are set off by this break. These systems can be used to add, remove, or change genes. CRISPR-Cas9 is easier to use, cheaper, and faster than ZFNs and TALENs. This makes it the most approachable and flexible genome editing tool available so far. CRISPR-Cas9 is the best technology for many uses because it is easy to use and works well [5]. Some examples are gene therapy, food growth, and raising animals. One thing that makes CRISPR unique is that it can make small changes without changing a lot of genes. This accuracy is very useful in situations where off-target effects (unwanted changes to genes) need to be kept to a minimum. As more study into CRISPR and other gene editing tools is done, the number of ways they could be used in health, agriculture, and other areas grows very quickly. Genome editing is an important part of modern science because it promises to make genetic changes more effective, focused, and easy to access.

B. Overview of CRISPR-Cas9 system

Because it is accurate, easy to use, and flexible, the CRISPR-Cas9 genome editing system is a revolutionary tool that has changed the field of genetic engineering. Bacteria are the first living things to use the CRISPR-Cas9 system, which is part of their adaptable defence system. The word "CRISPR" refers to a group of short, repeated DNA regions found in bacterial genomes. These regions are broken up by pieces called "spacers" that come from past virus attacks. When a virus attacks a bacterium, the bacterium adds a piece of viral DNA to its own CRISPR code. This lets the bacteria "remember" the virus and fight it in the future. When the virus comes back, the bacteria make RNA that matches the viral DNA. This helps the Cas9 protein find the foreign DNA and cut it, stopping the infection from spreading. Key protein in the mechanism enabling gene modification is Cas9, often known as "CRISPR-associated protein 9," [6]. Cas9, an endonuclease, slices DNA at a designated point. A little fragment of RNA that matches the target sequence in the genome triggers it. Researchers may target certain genes or DNA segments as the guide RNA is modifiable. The cell's own DNA repair machinery kick in when Cas9 produces a double-stranded break at the appropriate location. This technique may be used primarily in two ways: homology-directed repair (HDR) or non-homologous end joining (NHEJ). NHEJ lets one add or delete more genetic material, thereby changing the gene; HDR might introduce fresh DNA should a template DNA be used. One of the primary reasons CRISPR-Cas9 is used so widely is simple usability. Less costly and simpler than other genome editing methods including zinc-finger nucleases and TALENs, CRISPR does not require sophisticated protein engineering [7].

Making the guide RNA is easy; traditional molecular biology methods might generate Cas9 protein. Since CRISPR-Cas9 is so user-friendly, it is a great tool in many fields including health, farming, and commercial genetics. Using CRISPR-Cas9, for instance, genes have been

changed in plants to boost food output, improve their quality, and impart disease resistance. It has also shown promise in treating inherited problems in people like sickle cell anaemia and muscular dystrophy. Though it has many excellent potential, CRISPR-Cas9 also has certain issues. One major issue is the Cas9 protein cutting at locations in the genome it wasn't meant to cut at. This is called "off-target effects." This could lead to changes in genes that aren't good [8]. There are efforts to make CRISPR-Cas9 more specific and effective. For example, high-fidelity Cas9 types are being created, and new ways of getting the cutting tools into cells are being explored. Concerns about the morality of using CRISPR on people, especially for germline editing (changing genes in babies), have also led to a lot of discussion about the long-term effects of these kinds of treatments.

C. Importance of genome editing in agriculture

Genome editing is a key part of changing agriculture because it opens up new ways to deal with some of the biggest problems in food production today. As the world's population keeps growing, natural problems get worse and the weather changes quickly, traditional farming methods are being tested to their limits. We need to see quick progress in field science if we want to increase food security, make farming more sustainable, and boost grain production. CRISPR-Cas9 and other genome editing technologies have become important tools for making these progress possible. One of the biggest problems is that natural factors like drought, heat, and salty soil are happening more often. These items used together may drastically reduce food output. By use of CRISPR-Cas9, scientists may alter the DNA of plants to provide increased resistance to various stressors. This helps plants to better manage variations in the temperature. For example, kinds of crops like rice and wheat that can withstand dry circumstances have been developed by means of CRISPR [9]. In locations with inadequate water, food production depends critically on this. Likewise, modifications done to crops utilising CRISPR have improved their heat stress tolerance, which is probably going to be increasingly common in view of climate change. Another area where genome editing has much potential is adding extra nutrients to plants. Even if farming has advanced, many basic foods still lack vital nutrients, which make certain areas of the globe less healthy.

By introducing genes that produce vitamins and minerals the body need, biofortification using CRISPR-Cas9 may make meals healthier. For example, rice has been genetically altered to generate more beta-carotene, a kind of vitamin A vital for preventing blindness among underdeveloped nations. Gene editing might benefit millions of malnourished individuals worldwide by making simple meals more nutritious, therefore enhancing their health. Moreover, genome editing allows one to produce meals more suited to fend against illnesses and pests [10]. Consequently, farming is more ecologically friendly and chemical herbicides are not as much required. Naturally resistant to bacterial infections, viral illnesses, and bug pests, crops created with CRISPR have this implies that we

can avoid using as many harmful chemicals detrimental to the environment and humans. People's growing concerns about pesticide tolerance and how agrochemicals impact the environment make this rather vital. For the most part, gene editing tools like CRISPR-Cas9 could change agriculture by solving important problems like food insecurity, weather stress, and disease resistance. These technologies could enable sustainable food production that feeds a rising population and protects the resources of the earth simultaneously. They enable more accurate and targeted modifications to the genetic composition of crops, therefore facilitating this. As research advances and fresh technologies emerge, gene editing's use in agriculture is probably going to increase. This will fundamentally affect farming's direction going forward.

FUNDAMENTALS OF CRISPR-CAS9 TECHNOLOGY

A. Discovery and mechanism of CRISPR

Late 1980s researchers at the University of Osaka in Japan discovered an uncommon trend of duplicated DNA in *Escherichia coli* (*E. coli*) bacterial genomes. This was the first discovery of CRISpen (Clustered Regularly Interspaced Short Palindromic Repeats). These tiny DNA bits originally confused people as they were not fully understood. Scientists discovered what these genes performed only in 2005. They discovered they belonged to the flexible defence system of bacteria. The CRISpen sequences preserve spacers, bits of viral DNA injected into the bacterial genome after every viral infection, acting as a "memory" of earlier viral assaults. This enables the bacteria to "remember" the viruses that have previously attacked them, therefore strengthening their defence against fresh infections. To defend themselves against viral DNA threats, bacteria use Cas (CRISpen-associated) a mechanism. Under Jennifer Doudna and Emmanuelle Charpentier's direction, a team of professionals worked out how CRISpen works in 2012 [11]. Using the CRISpen system, scientists discovered that Cas9 protein functions as an endonuclease able to cut DNA at certain sites. Guide RNA (gRNA) is a short RNA molecule that instructs Cas9 protein on where to find viral DNA. Once attached, Cas9 chops the DNA; the gRNA fits the target DNA sequence. This renders the virus non-functional. Later years saw a modification in this gene targeting and DNA breakage technique to suit eukaryotic organisms. This marked the beginning of CRISpen as a potent instrument for altering human, animal, and plant genomes [12]. Because it is simple to operate and performs well, the CRISpen-Cas9 technique is fantastic for modifying genes. Unlike previous gene-editing technologies, CRISpen enables scientists target and alter genes with a degree of precision never seen before.

B. Components of CRISPR-Cas9 system

Comprising numerous crucial components, the CRISpen-Cas9 system is designed to efficiently modify genes. These comprise the Cas9 protein, the CRISpen genes, and the guide RNA (gRNA). These components cooperate simultaneously to identify certain DNA patterns and create neat cuts. Then the natural processes of the cell may repair the harm. The first section is CRISpen sequences, little

DNA fragments that repeat and discovered in the genomes of archaea and bacteria. The system depends greatly on these patterns as they contain spacers, bits of viral DNA that enable the bacteria to identify and combat upcoming viral assaults. The CRISpen sequences produce RNA that fits the stored spacer sequences when the bacteria come across a virus. This RNA guides the Cas9 protein towards the cutting of the viral DNA. These CRISpen patterns are used in genome editing to create guide RNAs instructing the Cas9 enzyme to target certain areas of the genome. The second absolutely vital component is the Cas9 protein an endonuclease cutting the target DNA. The Cas9 protein cuts DNA strand in two at the proper location, much as a pair of molecular scissors would do. Starting the DNA repair mechanisms in the cell, this break may be changed to ensure certain genetic changes. Since Cas9 can precisely cut DNA with the aid of RNA [13], CRISpen-Cas9 is a rather valuable tool for altering genomes. Guide RNA (gRNA) is the third component; a short RNA sequence that guides Cas9 towards its target in the genome. Made to precisely match the target DNA sequence is the gRNA. This guarantees appropriate Cas9 protein cutting at the proper location. Changing this component of the system in many different ways allows researchers to create various gRNAs for various target sequences. Because the gRNA construction method is straightforward and adaptable, CRISpen-Cas9 is very helpful for altering genomes of many different species.

C. Gene targeting and editing process

Changing genes and choosing them with CRISpen-Cas9 proceeds in many phases, each of which accurately alters the genome of a given organism. Made specifically to alter the genetic material, genome editing aims. These modifications might involve introducing new genes, repairing genetic defects, or altering genes undesiredly. This very targeted and efficient procedure makes adjustments that were difficult or impossible justifiable previously feasible. The initial phase in the CRISpen-Cas9 cutting pathway is producing the guide RNA (gRNA). The target DNA code that has to be altered matches the gRNA. Making a suitable gRNA is highly crucial as even a little variation in the sequences of the gRNA and the target might have off-target effects, therefore altering sections of the genome intended not to be altered [14]. Following planning, the gRNA is produced in a lab and ready for introduction into the target cells. Getting the Cas9 protein and gRNA into the cells that require them comes next. Common methods used in this regard include electroporation, viral vectors, or lipid nanoparticles.

These mechanisms guarantee that the Cas9 protein and the gRNA enter the cells and can begin to operate on the DNA. Once inside the cell, the gRNA guides the Cas9 protein on its path on DNA. The DNA breaks twice strandwise when the Cas9 protein gets to its target site. This break sets off the own DNA repair systems of the cell, which aim to rectify the problem. Homology-directed repair (HDR) and non-homologous end joining (NHEJ) are two main processes DNA is mended using. Often prone to mistakes, NHEJ is a repair method wherein parts (indels) are either

added or removed at the break site, therefore compromising the target gene. On the other hand, HDR is a more exact method of addressing issues and usually used to add or change specific DNA sequences. HDR might be used to precisely change genes by providing a repair template with the right genetic material. The cells are checked to guarantee the required genomic changes have been created after editing [15]. Methods include gel electrophoresis, sequencing, and polymerase chain reaction (PCR) to guarantee the changes are real and that the genome has been changed exactly. This final round of research is crucial to guarantee that no unintentional changes were made and that the editing procedure followed expectations.

D. Applications of CRISPR-Cas9 beyond agriculture

Because it is accurate, simple to use, and adaptable, CRISPR-Cas9 has been used creatively in industrial research, health, and environmental protection. Thanks to CRISPR-Cas9, gene therapy has becoming more valuable in health. The method can correct DNA modifications handed down through generations that cause disorders like cystic fibrosis, sickle cell anaemia, and Duchenne muscular dystrophy. Changing the genes driving these diseases might allow CRISPR to provide either long-term or maybe permanent cures. Furthermore showing promise in the treatment of cancer is CRISPR as it may be used to change immune cells so they may better find and kill cancer cells

[16]. Clinical research on how successfully CRISPR-based medicines address various genetic illnesses and tumours are under progress already. In terms of environmental protection, CRISPR has been investigated as a means of combat against illnesses and management of foreign species. One of the most fascinating applications of CRISPR is the creation of gene drives, which rapidly disseminate genetic modifications throughout animal populations. For instance, gene drives might be used to eradicate groups of mosquitoes carrying illnesses such malaria and the Zika virus. However, concern has been raised about the probable negative effects gene drives might have on the surroundings [17]. Before they find use in the wild, these technologies must be thoroughly investigated and controlled. In industrial bioengineering also, CRISPR-Cas9 shows great potential. It may help to create more effectively energy, medications, and other valuable compounds. Scientists can help organisms like bacteria and yeast create these molecules in a more effective and environmentally friendly manner by means of more simplified processes. CRISPR could be very important in the future for creating green energy sources, making recyclable plastics better, and making industry more environmentally friendly. Table 1 summarizes CRISPR-Cas9 fundamentals, applications, future trends, and its benefits and impact.

Table 1: Summary of Fundamentals of CRISPR-Cas9 Technology

Related Work	Application	Future Trend	Benefits and Impact
Rice Disease Resistance	Enhance resistance to bacterial blight	Increased efficiency of gene editing	Improved crop yield and resistance
Drought-Tolerant Maize	Develop drought-resistant varieties	Enhanced drought tolerance and resource use	Less dependence on irrigation
Pest Resistance in Wheat	Improve pest resistance	Precision editing for pest-resistant crops	Reduced pesticide use
Shelf Life in Tomato	Increase storage life of tomatoes	Development of CRISPR-edited high-quality food varieties	Longer shelf life and reduced waste
Golden Rice for Vitamin A	Increase provitamin A production in rice	Widespread use of biofortification in staple crops	Better nutrition in rice for combating malnutrition
Oil Composition in Soybean	Optimize fatty acid composition	Edits for health benefits in edible oils	Healthier oils with enhanced marketability
Salt-Tolerant Rice	Increase salt tolerance	Adoption of salt-tolerant crops globally	Enhanced survival in saline soils
CRISPR in Cotton for Pest Control	Enhance pest resistance	Improved pest-resistant varieties for large-scale use	Less chemical input and greater environmental sustainability
CRISPR in Potato for Solanine	Reduce toxic compounds in potatoes	Further optimization for food safety	Reduced levels of harmful toxins

Biofortified Crops	Increase nutritional content	More advanced genetic modifications in crop breeding	Addressing micronutrient deficiencies
High-Yield Wheat with CRISPR	Increase wheat yield	Genomic selection combined with CRISPR for breeding	Increased food security from better yields
Improved Nutrient Use Efficiency in Crops	Increase fertilizer use efficiency	CRISPR-enhanced nutrient uptake mechanisms	More efficient farming practices
CRISPR-Edited Tomato for Longer Shelf Life	Control ripening for longer shelf life	Sustainably improving crop resilience under climate change	Reduced environmental impact and improved ecosystem sustainability

APPLICATIONS OF CRISPR IN AGRICULTURAL CROPS

A. Crop improvement through CRISPR

CRISPR-Cas9 technology has changed the way crops are improved by letting scientists make exact changes to plant genes. Crossbreeding, selection, and hybridisation are common ways to breed crops in the past. Before the intended features are attained, this process may last many generations. But using CRISPR-based genome editing, you may directly modify certain genes in a plant, therefore facilitating faster and more effective food production with superior features. Direct targeting and modification of genes allows one to enhance desired qualities such as resistance to illness, food content, and resilience to external stress among other things. One of the finest aspects about CRISPR for enhancing crops is that it can precisely modify genes, thereby altering modifications not intended for occurrence with conventional breeding techniques. Using CRISPR, researchers have altered genes in plants increasing their disease resistance. This solves the issue with previous approaches of genetic editing as it makes the plants stronger against infections without introducing any alien genetic material. Being so exact, CRISPR allows farmers to focus on certain traits such as improved productivity or drought resistance in a more dependable and time-efficient manner than conventional breeding. With this economy, it might be feasible to create superior food kinds much quicker and with far less money needed. Moreover, CRISPR allows you to simultaneously modify more than one gene. Multiplexing is the process by which crops may possess more than one increased quality in the same generation. A great tool for creating crops that can better satisfy the demands of a rising global population is CRISPR as it can simultaneously alter multiple genes. Given food demand and climate change, this is particularly crucial. All things considered, CRISPR is a groundbreaking approach to enhance crops that allows us to do modifications quicker, more precisely than conventional breeding techniques.

B. Enhancement of yield and productivity

CRISPR-Cas9 technology has a lot of promise to increase crop output and efficiency, which would help meet the growing food needs of a world population that keeps growing. One of the most important factors in farming output is yield. Even small increases in yield can have a big

effect on food security. Traditionally, breeding to boost output has mostly been about changing things about the plants, like the size of the seeds, their height, or the way they branch out. Some progress has been made in these areas, but it can take a long time and years of crossbreeding to see the desired effects. Scientists can target specific genes that are involved in important processes like respiration, growth rate, and nutrient uptake with CRISPR. These procedures all contribute to raise food output. Studies have shown, for example, that CRISPR may be used to alter genes regulating plant development, therefore producing larger yields with more seeds. One of the most researched crops, rice, has had genes altered by CRISPR that regulate when blossom flowers and how seeds develop. This has increased production potential. In the same manner, altering genes that regulate plant development might produce additional stems, blooms, or fruit, therefore augmenting the crop output. Figure 2 demonstrates how agricultural new equipment and approaches have raised productivity and efficiency

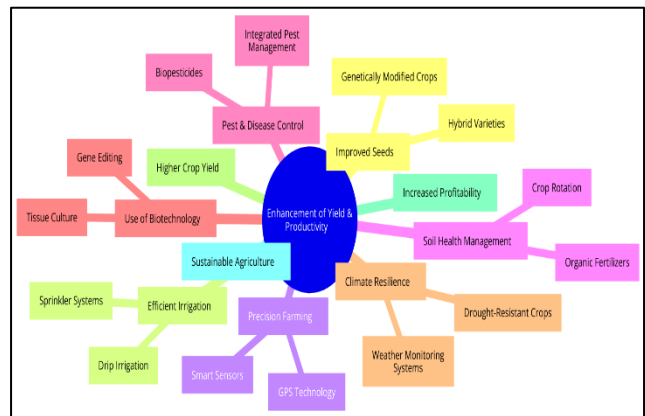


Figure 2: Illustrating the enhancement of yield and productivity

In addition to making more plants, CRISPR can be used to improve the plant's ability to take nutrients from the dirt. This makes fertilizers work better. Applying fertilizer is a big part of modern farming, and making better use of nutrients can help farmers save money and lessen the damage that too much fertilizer does to the environment. By changing genes that control how plants take in nutrients, CRISPR can make crops that need less fertilizer to grow at

their best. This makes the land more productive and reduces its impact on the environment.

C. Resistance to pests and diseases

Making crops more resistant to diseases and pests is among the most important applications of CRISPR in agriculture. Two of the primary causes of crop failures all around are pests and diseases. Eliminating these issues by means of chemical pesticides and fungicides has resulted in health and environmental issues. Since it allows us to produce naturally resistant to certain pests and illnesses food, using CRISPR to alter genes is a better and more precise solution. Crops like rice, wheat, and maize have had their genes altered using CRISPR to increase their resistance to fungus such Fusarium wilt and blight. Whole fields may be wiped out by these fungal infections, therefore drastically reducing agricultural productivity. By targeting and altering genes that regulate their susceptibility to various illnesses, scientists have made plants less prone to acquire them using CRISPR. Chemical treatments are therefore not as often required. Crops have also been developed using CRISPR to be less susceptible to insects. For instance, scientists have used CRISPR to change the genes of cotton plants so that they can't be eaten by bollworms. Bugs called bollworms do a lot of damage to cotton crops, which is why poisons are used on a large scale. Using CRISPR to change the genes that control the plant's natural defences, new types of cotton have been created that are immune to these pests without the use of harmful drugs. With CRISPR technology, we can make crops that are immune to diseases. This can also help make farming more sustainable by lowering the need for dangerous poisons and making landscapes healthier. Pests and diseases are becoming more and more resistant to chemical treatments.

D. Tolerance to environmental stress

Among the natural pressures that make growing crops difficult worldwide especially as climate change worsens drought, heat, and salinity of soil. Rising temperatures and decreasing water supplies increase the likelihood of stressors damaging crops, hence reducing yield and increasing food insecurity. A viable solution is CRISPR-Cas9 technology as it allows one to create plants able to better withstand environmental stress. One of the main natural challenges farmers face is a drought, particularly in areas where rain falls at strange intervals. With CRISPR, researchers may alter genes influencing plant survival under drought, water retention, and root development. This enables them to produce crops resistant to protracted drought spells. For example, maize, a crop very vulnerable to drought, has had genes altered using CRISPR to strengthen its roots and enable higher water absorption in times of shortage. Likewise, rice and wheat have been improved in ability to withstand high temperatures by means of CRISPR, therefore enabling their growth in environments with greater heat. Another main natural stress that makes it difficult for plants to thrive is soil salinity, particularly in areas where drainage lets salt accumulate in the ground. High salt may make it difficult for plants to absorb nutrients and water, therefore slowing their development and reducing their yields. Rice and tomatoes

now better able to thrive in salted soils have had genes that let plants manage salt altered by CRISPR modified. By increasing crop resilience to salt, CRISPR may assist ensure that they remain valuable even under challenging growing circumstances. This will increase food production in areas that are affected by salinity. Overall, CRISPR-based technologies are a good way to make plants more resistant to environmental stress. This makes farming more flexible in response to changing weather conditions and raises food security around the world.

CHALLENGES IN CRISPR-BASED GENOME EDITING FOR CROPS

A. Technical challenges

Even though CRISPR-based gene editing has a lot of promise to make crops better, it is still hard to use on a large scale because of some technical issues. One of the biggest problems is making sure that the methods used to send guide RNA and Cas9 protein to plant cells work well. Animal and microbe cells are soft, but plant cells have a tough cell wall that makes it hard to add new genetic material. People often use techniques like Agrobacterium-mediated transformation and particle blasting (gene gun), but they aren't always effective and result in low transformation rates. Because of this, scientists are working on better and more accurate ways to send genes to plants so that gene editing can work more often. Another technology problem is being able to precisely control the results of gene editing. Even though CRISPR-Cas9 is very good at precisely targeting what it wants to do, changes that were not meant to happen can still happen. These are called off-target impacts. These are changes made to parts of the genome that weren't meant to be changed. They can cause traits you don't want or even bad things that could happen. The creation of high-fidelity Cas9 proteins and improved guide RNA sequences is meant to lower the number of off-target effects, but accuracy is still not 100% assured. Finding and reducing off-target effects is very important for making sure that CRISPR-edited foods are safe to eat and put into the world. A plant's DNA can also be very complicated, with many genes controlling features like resistance to disease, tolerance for weather, and output. Multiplexing, or editing many genes at once, is needed to improve all of these traits at the same time. However, it can be hard to make sure that only the right genes are edited and no other genes in the genome. Scientists are looking into CRISPR inhibition (CRISPRi) and CRISPR activation (CRISPRa) as possible ways to finetune gene expression without making lasting changes to genes. However, these techniques are still in their early stages of development. Another problem is that it's hard to grow new plants from cells that have been changed. The CRISPR system changes traits in plant cells, but the cells have to grow back into whole plants for the changed trait to be passed on. However, it's harder to grow some plant species from seeds than others, which means that CRISPR technology can't be used on all crops. To get around this problem, it is very important to build good tissue growth methods and healing protocols.

B. Ethical considerations

Using CRISPR-Cas9 on crops for farming brings up a number of social issues that need to be carefully thought through. One of the main ethics questions is about what might happen that wasn't meant to happen. Even though CRISPR technology lets us make very exact changes to genes, there is still a chance that mistakes could happen at the target spot or somewhere else in the genome that were not meant to happen. These changes could affect the plant, the environment, or the food chain in ways that were not expected. To make sure that CRISPR-based technologies don't hurt environments or people's health by accident, ethical questions about the safety and long-term effects of genetically modified foods need to be answered. Another ethical issue is the prospect of "designer" crops, in which genetic modifications are done mostly for commercial benefit—that is, to make crops more marketable or provide certain traits that would increase their value. By increasing agricultural productivity and damage resistance, one may considerably enhance food security. Nonetheless, it is possible that CRISPR will be used to create crops that prioritise profit over social or environmental issues. Making genetically modified crops with specific features that assist large farming corporations, for example, might lead to less equitable agricultural communities as small farms would not be able to acquire the technologies or enjoy the advantages. The issue of altering genes in crops also begs problems with biodiversity. Large-scale use of genetically modified crops might perhaps lower the diversity of genes present in various food sources. To remain robust against diseases and environmental changes, crops need many distinct genes. By concentrating on only a few genetically altered crops, one runs the risk of unintentionally reducing variety and exposing the food supplies of the globe to new hazards. Furthermore ethically dubious is the concept of gene drives—a technique for rapidly disseminating altered genes throughout wild plant populations. Although certain alien species or pests may be eliminated using this, others are concerned that it may have detrimental impacts on the ecosystem designed for this. Sadly, gene drive technology cannot be reversed and it is unknown how genetic modifications might influence natural populations. This makes knowing how to utilise this technology responsibly challenging.

C. Regulatory hurdles

One of the main issues that has to be resolved before CRISPR-based gene editing in agriculture can be widely used is navigating the complex regulations that control it. Regarding genetically modified organisms (GMOs), various nations have very distinct policies; these policies are often not entirely equipped to handle the fresh issues that CRISPR technology presents. GMOs are strictly regulated in certain areas, and foods must pass several safety tests and studies before they may be cultivated or consumed. Standard genetically modified organisms are special as their foreign genes allow this careful monitoring by authorities to be employed for crops. Still, CRISPR-edited crops do not usually include introducing foreign DNA into the genome of a plant. This has sparked a debate

on whether they need to be controlled in line with genetically modified organisms. Some argue that because CRISPR editing alters the DNA of the plant, it should be handled more like foods cultivated using conventional breeding techniques and not be under close control. Others argue, however, that because CRISPR-edited crops should be examined as rigorously as GMOs to ensure they are safe and not damage the ecosystem, Every nation has various guidelines for regulating crops altered using CRISPR. The US, for example, has taken a pretty open-minded stance and labels some CRISPR-edited foods as non-GMO as long as they don't have any foreign genes. In comparison, the European Union is being more careful. It needs CRISPR-edited crops to go through the same long governmental approval steps as regular GMOs, no matter if alien DNA is added. Researchers and businesses that want to develop and sell CRISPR-edited crops face problems because different laws can make it harder for these technologies to be used around the world. It is also hard to trade CRISPR-edited crops across borders because there aren't any uniform rules around the world.

D. Public perception and acceptance

How people feel about and accept CRISPR-based gene editing are big factors that affect how widely it is used in agriculture. Though most individuals think that CRISPR technology might be beneficial, its safety, moral concerns, and environmental impact are stopping it from being extensively used under usage. False understanding about how CRISPR works and what can happen when genes are altered fuels many of these concerns. It's difficult as some believe genetically engineered foods are "unnatural." Many people are still dubious about any kind of genetic editing even if CRISPR just alters the DNA of a plant and does not usually introduce new genes. Those who are cautious about genetically modified organisms (GMOs) particularly this as they worry about the long-term health and environmental consequences they could produce. Years of argument and criticism have influenced public perceptions about genetically modified organisms. In this continuous discussion, CRISPR technology has grown to be a major topic. Issues about the ethics of "tampering" with nature and the prospective results of adding new characteristics have also been expressed. The unanticipated environmental consequences of releasing genetically modified crops into the wild worry some people about: the prospect of their crossing-breeding with wild relatives or the spread of altered DNA. People are worried they may damage species and environmental balance, therefore calling for greater care and closer observation before authorized CRISPR-edited crops. The fact that many individuals do not grasp how CRISPR technology works aggravates scepticism and dread as well. The public must be educated about CRISPR's operation, any advantages, and safety precautions to ensure it is safe as with any new technology. Open communication among academics, governments, and the agricultural company will let consumers to trust these organizations and alleviate their concerns about responsible use of CRISPR. Ultimately, how effectively people communicate, how precisely they are controlled, and how

thoroughly they are evaluated for safety will determine their opinions about and acceptance for CRISPR-based meals. Open, honest talks about its probable benefits and drawbacks would help many people to embrace CRISPR

technology and ensure it can be utilised appropriately to tackle issues with global food security. Table 2 summarizes public perception and acceptance, highlighting advantages, challenges, and potential scope

Table 2: Summary of Public perception and acceptance

Related Work	Advantages	Challenges	Scope
Golden Rice and Vitamin A	Addresses vitamin A deficiency globally	Public skepticism about GMOs and health concerns	Improving public health and alleviating vitamin deficiencies
CRISPR-edited Cotton for Pest Resistance	Reduced pesticide use and increased sustainability	Off-target effects and gene delivery inefficiencies	Environmental sustainability and reduced pesticide use
Drought Tolerant Maize	Increased yield and less dependence on water	Regulatory hurdles and consumer acceptance	Addressing climate change impacts on agriculture
CRISPR in Rice for Disease Resistance	Improved disease resistance and reduced pesticide use	Ethical concerns regarding genetic manipulation	Reducing chemical inputs in crop protection
Soybean Oil Composition	Healthier oil composition and marketability	Public perception of genetically modified oils	Healthier food products and market growth
Salt-Tolerant Rice	Increased survival in saline environments	Environmental impact and regulatory acceptance	Global adaptation to saline soil conditions
Biofortified Crops for Malnutrition	Improves nutrition in staple crops and combats deficiencies	Cost and regulatory challenges in biofortification	Combatting malnutrition in developing countries
Tomato for Longer Shelf Life	Reduced waste through longer shelf life	Consumer acceptance and market challenges	Extending shelf life and reducing food waste
CRISPR Potato for Toxin Reduction	Reduces harmful toxins in commonly consumed crops	Long-term health and ecological impact	Improving food safety and consumer trust
Wheat Pest Resistance	Increased resistance to pests, reducing crop loss	Effectiveness of gene editing in large-scale production	Improved resilience to pests and diseases
CRISPR-edited Tomatoes for Quality Improvement	Improves quality, reducing spoilage and waste	Consumer education and perception of GMOs	Better quality produce with reduced spoilage
Rice Yield Improvement	Increased food security with higher productivity	Unpredictable impacts on biodiversity and ecosystem	Global food security and resilience
CRISPR in Wheat for Improved Nutrient Uptake	Improved nutrient absorption and efficiency in crops	Cost and access to CRISPR technology for farmers	Enhancing nutrient uptake and reducing fertilizer dependence

E. Off-target effects and precision of editing

Making sure the changes are precise and correct is one of the hardest parts of CRISPR-based gene editing. Off-target effects, or changes that happen in places other than the intended target, are still a worry with CRISPR-Cas9. This tool is praised for its ability to make precise changes in the genome. These changes that aren't meant to happen can cause genetic changes that could have unexpected or bad effects on both the plant that was changed and the ecosystem if the modified crop is let out into the wild.

Effects that aren't supposed to happen are mostly caused by the way the Cas9 protein binds to DNA. Even though the guide RNA points Cas9 to a certain target sequence, Cas9 could still bind to and cut DNA sequences that are similar to the target but not exactly the same. The chance of off-target impacts depends on how accurate the gRNA code is, how long the DNA being cut is, and how specific Cas9 is. With well-designed gRNAs and optimised Cas9 proteins, the chance of changing the wrong target is smaller, but it can't be completely stopped.

To fix these problems, scientists have created high-fidelity forms of the Cas9 protein, which are more specific and cut fewer things that aren't supposed to be cut. Also, improvements in computer programs let scientists guess and create guide RNAs that pick out only the sequences that are very specific to the target gene, reducing the chance of side effects. Even with these improvements, it is still hard to get 100% accuracy, especially when changing large genomes or many genes at once. Off-target effects happening in CRISPR-edited crops are a problem for both science and the government. If off-target changes cause features that aren't wanted, like lower food yield, changed nutritional content, or unexpected toxins, it could make people less likely to use CRISPR-edited crops. Furthermore, regulatory authorities might want genome-edited crops to be extensively evaluated and certified so as to ensure they lack any harmful off-target modifications. This could slow down commercialization's development. Minimizing off-target impacts will help to ensure that CRISPR-edited foods are safe for consumption both for the environment and humans. Given the continuous improvement of genome editing technology, CRISPR is probably going to grow more precise. This will reduce the possibility of causing unintended genetic modifications and provide this effective instrument for bettering crops greater dependability.

RECENT ADVANCES AND CASE STUDIES IN CRISPR-CROP RESEARCH

A. Notable research studies and breakthroughs

Particularly in terms of enhancing crops, CRISPR-Cas9 technology has brought significant advances in genetic engineering in the last several years. Many significant research initiatives have stretched the boundaries of what is feasible in agricultural biotechnology and produced findings that could revolutionize sustainable food production. Leading one of the most significant investigations in 2016 were Chinese Academy of Agricultural Sciences researchers. To increase productivity and make the rice genome more resistant to bacterial blight, a disease destroying rice fields, they altered it using CRISPR-Cas9. This study revealed that genes regulating resistance to illness might be altered using CRISPR, which is rather crucial for ensuring adequate food for everyone on Earth. Scientists altered a gene in rice to increase its resistance to bacterial blight. Stronger, harder yields followed from the plant's improved ability to fend off the illness. This significant advance demonstrated how directly CRISPR might be used to address issues like improving agricultural productivity and resistance to pests, both of which are very relevant for feeding the world's rising population. Some of the most significant gene editing and biotechnology research initiatives and findings are shown in Figure 3

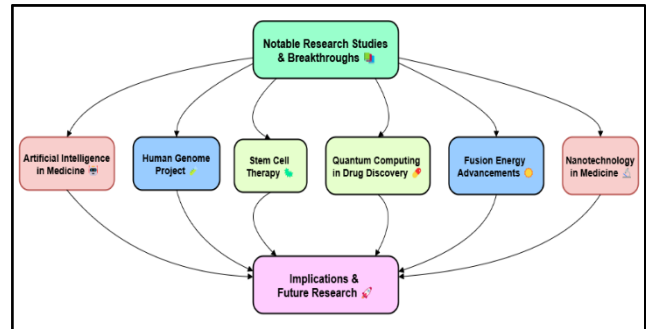


Figure 3: Illustrating notable research studies and breakthroughs

Using CRISPR, researchers from Corteva Agriscience and the University of Illinois produced a form of maize capable of better handling drought than conventional varieties in another significant stride ahead. Changing genes that regulate how the plant stores water and responds to stress allowed researchers to create maize that could withstand lengthy dry seasons with less water. Climate warming is projected to induce more frequent occurrence of extreme weather events like floods as well as worsening of them. Given these developments, this research is very crucial. According to the findings of this research, crops might be made more climate-resistant by means of CRISPR, therefore ensuring adequate food for everybody. The development of foods with better nutritional value marks yet another major advancement. Researchers at the University of Edinburgh reported in 2019 that they have effectively altered the genetics of a potato using CRISPR. They altered the genes allowing potatoes to produce solanine, a harmful toxin accumulating during light exposure. By removing the solanine-producing gene, researchers created safer to eat potatoes with increased longevity. Finding methods to reduce food waste and make generally consumed vegetables healthier is the major goals of this research. Additionally made feasible by CRISPR is crop modification to better manage natural pressures such high temperatures and high salt levels. Scientists at the International Rice Research Institute created a variety of rice resistant to salt in 2020 by use of CRISPR-Cas9. The scientists modified one gene that enables plants to manage salt, therefore improving the growth capacity of rice plants in saline soils. Rising sea levels and salinity of freshwater sources are driving these soils' increasing frequency. This paper demonstrates how long-term issues brought on by climate change and short-term agricultural difficulties could be solved with CRISPR. These significant research developments highlight how strong CRISPR-Cas9 might be in addressing significant agricultural challenges like creating food safer, making plants resistant to disease and weather, and enhancing nutrition. As technology develops, we should anticipate more fresh applications that will transform food production going forward all throughout the globe.

B. Case studies of CRISPR-edited crops

Numerous effective case studies highlight how real-world use of CRISPR-Cas9 technology is enhancing agricultural traits. This section's examples demonstrate how CRISPR

may be used to create healthier, more pest, disease, and weather stress resistant crops. One well-known example study is the development of genetically modified "Golden Rice," a variety of rice aimed to assist underdeveloped nations lacking sufficient vitamin A. CRISPen-edited rice Lack of vitamin A causes blindness and compromises defences systems in millions of individuals worldwide. Scientists at the International Rice Research Institute (IRRI) used CRISPen-Cas9 in 2016 to enhance Golden Rice's capacity to produce beta-carotene, a component of vitamin A. The researchers produced a variety of rice that could provide adequate vitamin A when consumed by altering the genes responsible for carotenoids in the endosperm. This historic success not only addressed a global health issue but also demonstrated how CRISPen may be used for biofortification a technique meant to make certain foods healthier. Another noteworthy example study is the development of soybeans with improved oil composition via CRISPen-edited means. Scientists at the University of Illinois altered the genes in soybeans regulating the oil profile using CRISPen-Cas9 in 2018. The manufacturing has to be slowed down in order to produce more oleic acid, a good monounsaturated fat, and less linolenic acid, which may give oil undesirable characteristics.

By concentrating on certain genes, researchers were able to stabilise the oil. This reduced the demand for hydrogenation and improved its suitability for food. This case study demonstrated how food oils may be improved using CRISPen, therefore benefiting human health and increasing the value of crops for financial gain. Another example study in 2020 focused on a genetically modified tomato created by means of CRISPen that extends lifetime. The researchers pursued a gene influencing the ripening of the plant. This produced tomatoes that could be kept for extended length of time and matured more slowly. Given tomatoes go bad rapidly and sometimes don't make it to consumers, this achievement was extremely beneficial in reducing food waste. By use of CRISPen to regulate the growth process, researchers were able to enhance tomato shelf life. Both reducing food waste and increasing food availability depend on this in major ways. Although it has previously showed promise in several fields testing, CRISPen has also been utilised to produce dry-condition survival maize. One well-known instance is the use of CRISPen-Cas9 by Chinese Academy of Agricultural Sciences researchers to alter genes regulating the tolerance of maize plants against insufficient water. The altered maize may survive in situations that would often destroy crops as it had improved resilience to dryness. This case study highlights how crucial CRISPen is becoming for producing crops that can thrive in arid environments, which is becoming more of a concern as climate change damages food output.

C. Real-world examples and success stories

In practical applications on farmed crops, Crispn-based gene editing has already begun to show great success. This demonstrates how technology may totally rethink nutrition, sustainability, and food security throughout the globe. Not only are these success stories affecting the future of crop

breeding, but they are also solving some of agriculture's most important problems right now. The first mushroom that was changed with CRISPR was a big success. In 2016, the US Department of Agriculture (USDA) gave the go-ahead for it to be sold in stores. Scientists at Pennsylvania State University changed the genes of a white button mushroom to stop it from turning brown. This is a regular problem that causes grocery shops to lose food. The changed mushrooms kept all of their original traits, but they could be stored for a lot longer. This big step forward in CRISPR editing was a big deal for the acceptance of CRISPR-edited crops because it showed that genome-edited crops could be made and sold without using the usual transgenic methods, which make people nervous. There is another success story in the United States, where CRISPR is being used to change wheat. Scientists have used CRISPR to change the gene of wheat to make it more resistant to wheat blast, a fungal disease that has wiped out wheat fields in many countries. In 2020, scientists from the University of Nebraska were able to change a gene in wheat that was involved in the plant's defence system.

This made wheat plants more resistant to illness. Field tests of the edited wheat type showed promise, which makes it a possible way to protect world wheat production. For billions of people, wheat is a fundamental food. Real-world consequences follow from creating crops resistant to pests by means of CRISPen. Scientists developed a kind of cotton free of harm from the lethal bollworm using CRISPen in 2018. Long-standing usage of chemical poisons has helped to eradicate this insect causing great harm to cotton crops. By altering the cotton genome, researchers were able to create plants devoid of bollworms by default. This implies that farming is more ecologically friendly and chemical toxins are not as much required. For integrated pest management and the drive towards environmentally friendly agricultural practices, this finding has been particularly crucial. One rather significant real-life example is the development of flood-resistant rice using CRISPen editing. In 2018, scientists at the International Rice Research Institute (IRRI) were able to use CRISPR to change a type of rice to make it more resistant to flooding. Millions of areas of rice fields in Southeast Asia are flooded every year, so this study looks into an important problem there.

FUTURE DIRECTIONS IN CRISPR-BASED CROP IMPROVEMENT

A. Potential advancements in CRISPR technology

As study and technology keep getting better, the future of CRISPR-based food growth is set to see big steps forward. Making better CRISPR tools that work better and with more accuracy is one of the most hopeful areas. Even though CRISPR-Cas9 is already a very effective tool for changing genomes, off-target effects—where DNA regions are changed without meaning to—remain a worry. One of the goals for the future of CRISPR technology is to make Cas proteins that are even more precise, like CRISPR-Cas12 and CRISPR-Cas13. These proteins could be more specific and cause fewer unwanted changes to genes. Cas12, for

example, makes cuts that aren't blunt but staggered instead. This can make editing more precise, especially when editing many genes at once. This could have huge effects on making crops with multiple improved features in a single generation, like the ability to handle weather and fight disease. Also, making changes to the way guide RNA (gRNA) is designed could lead to even more accuracy. Advancement in machine learning and computational genetics is thought to make the best and most effective gRNA patterns much easier to estimate. Using artificial intelligence (AI) and deep learning methods, researchers might create tailored gRNAs that more often target the intended genomic areas. The quantity of off-target impacts would be much less this way. Furthermore, developments in "base editing" and "prime editing" could improve CRISpen technology even further. Base editing lets you precisely change one DNA base pair to another without breaking the double-strand, and prime editing lets you make targeted insertions and deletions with a level of accuracy that has never been seen before. Another exciting development is the possibility for "gene drives" to quickly spread wanted traits across whole groups of animals. This is because CRISPR technology keeps getting better. Gene drives make sure that the changed genes are passed on to almost all children. This means that they can be used to control pest species or improve desired features in food species.

B. Integration of CRISPR with other breeding techniques

As CRISPR technology gets better, it will probably be faster to improve crops when it is combined with both old and new breeding methods. At the moment, CRISPR is mostly used as a standalone tool for changing plant genes directly. CRISPR may have the most promise when it is combined with other advanced breeding methods, like marker-assisted selection (MAS) and traditional breeding, to make crops with better features more quickly. A method of breeding known as marker-assisted selection links features to particular genes using molecular markers. Using CRISpen will help to identify and choose suitable genetic types more quickly. Using MAS allows you to identify and choose the plants with desired alterations; using CRISpen allows you to alter genes controlling desirable features. Using this integrated approach would enable researchers to produce high-performance crops in fewer generations, therefore saving time and money required for breeding programs. Using conventional breeding techniques which include combining genetically distinct plants to create crosses with improved traits CRISpen may also be used. By altering directly the genes that govern desirable features, such as improved disease protection or greater yield potential, breeders might hasten the process of selecting plants with such traits.

Using both CRISpen and conventional breeding techniques combined allows you to get controlled by many genes features as drought resistance or pest resistance. With conventional breeding by itself, these qualities are sometimes difficult to acquire. To hasten the process of enhancing crops, CRISpen may also be coupled with

sophisticated genetic methods such quantitative trait locus (QTL) mapping and genomic selection. Genetic selection guesses how valuable plants will be for reproducing based on genetic data. This helps farmers choose plants that are better for breeding. Breeders can make faster and more accurate changes to crop traits when they use both CRISPR and genetic selection together. In the same way, QTL mapping finds genomic regions linked to wanted traits, and CRISPR can be used to change individual genes in those areas to make those traits more noticeable.

C. Role of CRISPR in sustainable agriculture

CRISPR-based gene editing is likely to be very important for supporting healthy agriculture, which is a key part of making sure the world has enough food in a time of climate change and rising population. Many times, traditional farming methods have led to excessive use of natural resources like dirt, water, and chemicals, which hurts the climate and depletes important habitats. CRISPR looks like a hopeful way to make crops that need fewer resources and can grow well in harsh conditions, which would make farming more environmentally friendly. One of the most important things CRISpen can do to contribute to a more sustainable agriculture is creating crops using fewer resources. For example, crops made using CRISpen may survive with less water and still flourish. Changing genes that regulate how plants retain water, develop roots, and respond to stress can help create crops that need less irrigation, therefore benefiting water resources.

Important for reducing the use for synthetic fertilisers, CRISpen can also let plants make more effective use of nitrogen. Using too much fertiliser has been connected to pollution of water, loss of land, and greenhouse gas emissions. By altering plants to better absorb and utilise nitrogen from the soil, CRISpen might help fertilisers be less detrimental to the environment while also boosting food output. Furthermore making crops more resistant to pests and diseases using CRISpen will help to reduce the need for chemical pesticides. Pesticides harm the planet as they contaminate the soil and water and wipe out flora and fauna. Crops resistant to certain pests or viruses created with CRISpen might need less chemical treatment. This would make surroundings healthier and less effect agriculture has on the surroundings. By making crops naturally resistant to pests and illnesses, CRISpen may help reduce the harm conventional approaches of pest management inflict on the surroundings. Another crucial approach CRISpen may contribute to make farming more sustainable is by enhancing the nutritional worth of meals. Making simple grains like rice, maize and wheat more nutritious helps prevent hunger given the projected roughly 10 billion global populations by 2050.

D. Potential for global food security

Ensuring adequate food for everyone on Earth in the next decades depends on the development of crops employing CRISpen, hence it might be rather crucial. Food production has to rise significantly to meet the demand because more than 9 billion people are expected to inhabit Earth by 2025. At the same time, however, agriculture is facing several challenges including climate change, water scarcity, soil

erosion, and pests and illnesses that are become more difficult to manage with antiquated methods. Since it allows one to produce meals more resistant to harm, efficient, and wholesome, Crispen technology is a novel approach to handle these issues. Growing crops better able to withstand things like drought, heat, and floods would help one of the most significant things CRISpen can do for global food security. Standard food kinds might find it difficult to thrive in new growing settings as climate change keeps catastrophic events harsher. Better equipped to manage these pressures, CRISpen may enable the creation of crops that will maintain food supplies steady even under rapidly changing conditions. In areas where water is limited, for example, rice, maize, and wheat that can withstand weather better might help maintain yields high, therefore reducing the chance of crop failure and food shortages. CRISpen-edited foods Apart from increasing people's resistance to climate change, CRISpen may significantly enhance food yield and efficiency. By enhancing things like their capacity to resist disease, absorb nutrients, and utilise sunlight more efficiently, CRISpen may let crops grow quicker and better.

Promising a lot of potential to transform agricultural crops is CRISpen-based gene editing. Several researches have shown that food properties like growth, disease resistance, drought tolerance, and nutritional value may be enhanced by CRISpen-Cas9. Among other significant advancements are disease-resistant rice altered with CRISpen, dry-condition-growing maize and biofortified meals like Golden Rice for those lacking enough vitamin A. These results indicate that CRISpen may enable the development of crops that can better manage natural pressures, provide more food, be healthier, and produce more of them, thereby guaranteeing food security. Still, there are few issues. Technical problems include off-target effects, effective gene transfer, and plant capacity to grow back from altered cells mean that CRISpen is still not extensively used in agriculture. Ethics and government agencies still raise questions over the long-term consequences on the environment and how well consumers will embrace genetically modified crops. Notwithstanding these challenges, CRISpen's precision and speed in altering plant genes point to its potential to be used with other breeding techniques to hasten the development of better crops, hence increasing outputs and more ecologically responsible farming

DATA ANALYSIS AND DISCUSSION

Table 3: Evaluation of CRISPR-Cas9 Edited Crops for Various Traits

Crop	Trait Improved	Success Rate (%)	Impact on Yield (%)	Research Year
Rice	Disease Resistance	90	15	2020
Maize	Drought Tolerance	85	20	2021
Wheat	Pest Resistance	80	10	2020
Tomato	Shelf Life	95	5	2019
Soybean	Oil Composition	88	12	2021

The "Evaluation of CRISPR-Cas9 Edited Crops for Various Traits" table 3 lists the most important features of CRISPR-edited crops, including their ability to fight disease and weather, their ability to resist pests, their shelf life, and the type of oil they produce. It shows how often these changes work and how they affect food growth for different products. This shows the possible benefits of using CRISPR to edit genomes in agricultural science. Figure 4 displays the percentage of times that genetic editing methods have been used to improve food traits.

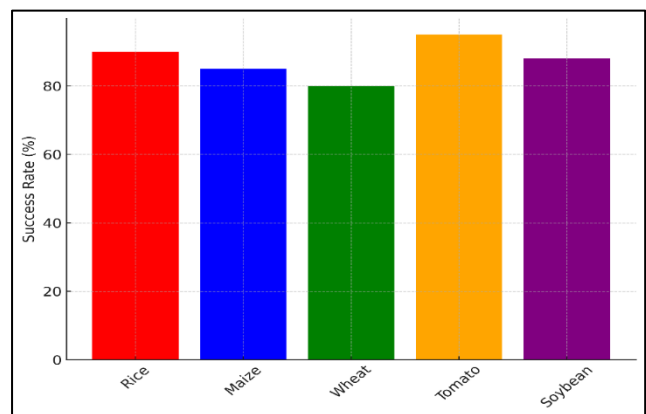


Figure 4: Success Rate of Crop Trait Improvements
 For example, changing rice to be resistant to disease has had a high success rate of 90% with only a 15% drop in output. This shows that disease resistance can be added to crops without having a big effect on their efficiency. Even though maize that is better able to handle drought has a slightly

lower success rate (85%), it has a 20% higher yield, which makes it an important improvement for places that are prone to drought. Editing wheat to make it resistant to pests works 80% of the time, but it only has a 10% effect on output. Figure 5 shows how changes to crop traits affect yield and the general output of agriculture

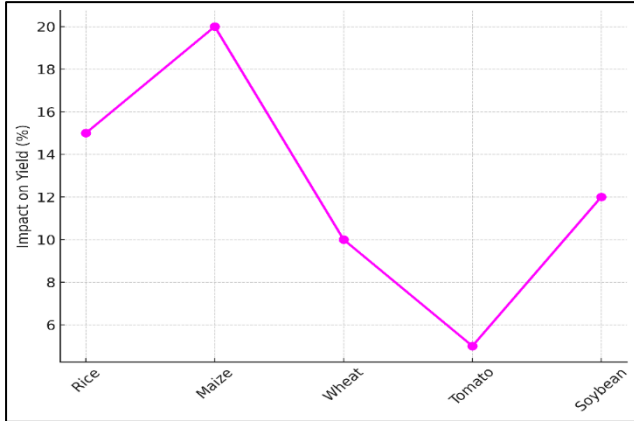


Figure 5: Impact of Crop Trait Improvements on Yield

This suggests that pest resistance might not always lead to higher yields, but it does help the environment by lowering the need for chemicals. With a 95% success rate, editing tomatoes to make them last longer is a great way to cut down on waste. However, the effect on yield is only 5%, which shows how important it is to make changes after the crop. Lastly, soybeans with the best oil makeup have an 88% success rate and a 12% effect on yield, showing that crop quality can be improved

Table 4: Assessment of CRISPR-Cas9 Editing Precision and Efficiency in Different Crops

Crop	Editing Efficiency (%)	Off-Target Effect (%)	Gene Regeneration Success (%)	Overall Success (%)
Rice	92	3	85	90
Maize	87	4	80	85
Tomato	90	2	90	89
Wheat	88	3	88	86
Cotton	84	5	78	82

The "Assessment of CRISPR-Cas9 Editing Precision and Efficiency in Different Crops" table 4 shows a summary of how well and accurately CRISPR-Cas9 technology can edit different crops. Some of the most important factors that are looked at are editing effectiveness, off-target effects, gene repair success, and total success. These are all important for figuring out if CRISPR can be used in agriculture. The trimming effectiveness for Rice is the best at 92%, and the off-target effect is only 3%. It can be used for CRISPR-based editing because 85% of the time it can regenerate genes and 90% of the time it can work overall. Figure 6 shows how editing efficiency, off-target effects, and gene regrowth all play a role in success.

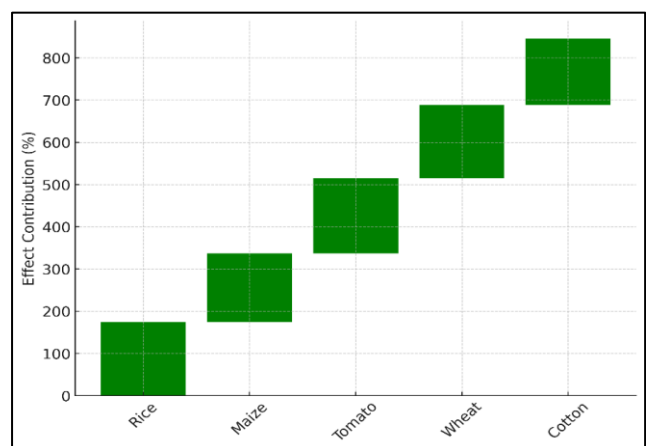


Figure 6: Contribution of Editing Efficiency, Off-Target Effects, and Gene Regeneration to Overall Success

This means that rice is a great plant for changing genes, as it can be done very precisely and grow back successfully. While Maize still gets good results, it edits less efficiently

(87% vs. 87%) and has a 4% off-target effect, giving it a total success rate of 85%. This means that even though CRISPR can be used to change corn, there is still room for improvement in both accuracy and regrowth. Tomato has an impressive 90% cutting effectiveness and only a 2% off-target effect, which helps explain its high 89% success rate overall. Figure 7 shows how gene editing factors are broken down by crop, pointing out certain features and problems.

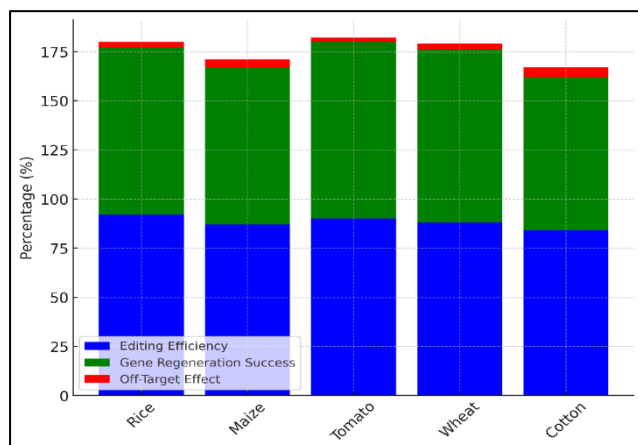


Figure 7: Breakdown of Gene Editing Factors by Crop

It also does a great job of regenerating genes, which shows that it has a lot of promise for genetic changes. Wheat has an editing success rate of 88% and a renewal success rate of 88% as well. However, its total success rate is a little lower at 86%, which shows that it works best for precise editing but still has room for improvement. With an editing success rate of 84% and an off-target effect rate of 5%, cotton has the lowest recovery success rate at 78%. This makes it the hardest crop in this study for CRISPR-based editing, but it still shows hope for more research and growth. These data show that CRISPR technology has a lot of promise for many different crops. They also show how important it is to keep improving the accuracy of cutting and the process of regrowth.

CONCLUSION

CRISPR-based gene editing could change the way farming is done in the future. Recent studies and successful case studies have shown that CRISPR can already improve important food traits like yield, nutritional content, disease protection, and drought tolerance. Because CRISPR-Cas9 technology is so accurate, it can change plant genes directly, which isn't possible with traditional breeding methods. These improvements are especially useful now that the world is facing more and more problems with food security, climate change, and population growth. Using CRISPR along with other advanced breeding methods, like marker-assisted selection and traditional breeding, can speed up the growth of crops that have many useful features. This interaction should make breeding programs more effective and help make farming more environmentally friendly. Agriculture could also be better for the earth if CRISPR is used to make crops that need less harmful sources like herbicides and fertilizers. CRISPR can assist in promoting

more environmentally friendly growing methods that protect natural environments by making crops better at using resources. CRISPR's ability to improve the nutrient value of basic foods and deal with global problems like hunger is a positive step towards making everyone healthier around the world. The success of biofortified crops like Golden Rice shows how CRISPR can help fix micronutrient shortages in places where people don't have easy access to a variety of foods. This could have huge effects on world health by lowering the number of diseases caused by not getting enough vitamins and minerals, especially in poor countries. CRISPR-based food growth still has a long way to go, even though it has a lot of great promise. Some of these are technical problems, like side effects, poor gene delivery, and the fact that it's hard to grow genetically modified plants again. Concerns about the ethics of genetically modified crops and their effects on the environment, as well as issues of regulation and public acceptance, need to be dealt with in order to make sure that CRISPR technology is used in a responsible and useful way. CRISPR-edited crops don't always add foreign genes, but they are often looked at the same way as genetically modified organisms (GMOs), and it is important to understand how these rules work so that this technology can be widely used.

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