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Review Article

Improving the Genetic Traits of Crops to Cope with Environmental Conditions

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Abstract

The world today faces unprecedented challenges in achieving food security for a continuously growing population amid escalating climate change, from rising temperatures to water scarcity, land degradation, and increasing soil salinity. It has become clear that traditional crops are no longer able to withstand these environmental conditions on their own, and here the role of modern science in improving the genetic traits of crops stands out, with the aim of developing new varieties capable of surviving and producing even in the harshest conditions. Gene modification is not just a technological option but has become an inevitable necessity to ensure the continuity of agricultural production and achieve food security in the future.

Keywords: Crop improvement, food security, genetic engineering, sustainable agriculture.

Introduction

Out of urgent necessity in an era of climate disruption, as the world enters a phase of unprecedented climatic fluctuations, expectations are increasing that the yields of major crops such as wheat, rice, and corn (1) could decrease by 20-30% by 2025, while the demand for food rises by a similar percentage (2). The term 'producing more using fewer resources' is the greatest challenge facing researchers in the field of plant breeding (3). Traditional improvement standards and the efficiency of resource use in production are no longer sufficient; it has become necessary to focus on environmental flexibility and Resource Use Efficiency (4). Improving genetic traits is not just about modifying plant genes, but it is engineering a complete biological system, such as abiotic stress, including heat, drought, and salinity, and biotic stress, including agricultural pests and diseases, whose severity and interactions are exacerbated under rapidly changing climate conditions (5). Facing this complex challenge requires a radical departure from traditional education approaches that focused on the productivity of the variety under optimal conditions, towards adopting strategies aimed at educating agricultural systems rather than just improving varieties (6). Plants in the field face, at the same time, heat waves that occur during flowering, drought seasons that last longer or shorter than expected, and soil salinity accumulation due to irrigation methods, alongside increasing biotic pressures from insects and diseases that were previously geographically confined. Therefore, a single hereditary trait that provides tolerance to one stress factor is no longer sufficient (7). The solution requires " Integrative Resilience" designing

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metabolic and genetic networks that give the plant unprecedented integrative resilience by combining genomics, physiology, computational modeling, and artificial intelligence to accelerate the discovery and editing of genetic pathways that control water and nutrient use efficiency under variable conditions, while maintaining the broad genetic basis that ensures genetic stability across different environments (8). And here emerges the central question that this article will seek to answer: how can precise genome engineering, coupled with innovative agricultural systems, turn the challenge of producing more with fewer resources into a real opportunity to achieve food security in the era of climate disruption?

The concept of improving genetic traits and its importance

Genetic improvement refers to the use of principles of genetics and genetic engineering to change the genetic makeup of plants so that they acquire desirable traits they originally did not have or enhance existing traits to be more efficient (9). The importance of this specialty lies in its ability to provide radical solutions to chronic agricultural problems such as drought resistance, salinity tolerance, pest and disease resistance, and improving the efficiency of water and nutrient use (10). Improving genetic traits directly contributes to reducing agricultural losses and increasing productivity per unit area, which is known as the concept of sustainable productivity (11). This concept is not limited to increasing yield only, but also includes preserving natural resources for future generations, reducing environmental degradation, and ensuring economic viability for producers (12). Improving genetic traits, when managed properly, can achieve the difficult balance between meeting the present food needs and not compromising the ability of the future to meet its needs (13). And to achieve this balance, it is necessary to understand that improving hereditary traits is not a simple linear process, but rather a complex interaction between several levels:

Level One: Genetic Diversity as Raw Material

No trait can be improved without the existence of basic genetic diversity from which selection can be made or modifications can be introduced. This means that preserving gene banks and the wild sources of crop relatives is not an academic luxury, but a strategic line of defense. The gene we need today to resist a new disease or withstand an unprecedented heatwave may be hidden in a wild variety whose importance we never imagined. Therefore, the erosion of genetic diversity due to the expansion of cultivation of a limited number of high-yield varieties represents a silent threat to long-term food security (14).

Level Two: The environment in which the gene expresses itself

The desired gene does not work in a vacuum but interacts with the surrounding environment (soil, climate, microorganisms, pests) and with the background, so any improved variety may be a superhero (G×E×M) management × environment × plant genetics. This is what is known as gene interaction under laboratory or greenhouse conditions, but it fails in the field when facing real climate fluctuations or multiple stresses at the same time. Therefore, intensive field evaluation stages in multiple sites and climates are not just a routine procedure but an essential requirement for the success of any breeding program (15).

Level Three: Accompanying Agricultural Management

Even the best genetically improved varieties will fail if placed in an unsuitable agricultural system. Depleted soils, inappropriate planting times, incorrect irrigation methods, and suboptimal planting densities are all factors that can turn a promising variety into a disappointment. This means that genetic trait improvement should be part of an integrated technical package that includes advisory recommendations for farmers, rather than a standalone magic solution (16).

Techniques used in improving genetic traits

There are multiple methods and techniques used by scientists to improve the genetic traits of crops, and these techniques range from the very traditional to the very modern, as follows:

1. Traditional selection and hybridization: Although this method is old, it still forms the basis of breeding programs and relies on selecting plants with good traits and hybridizing them to obtain offspring that combine the best traits, but this method requires a long time and may result in desired traits being replaced by undesirable traits. This method relies on the principle of natural recombination of genes during sexual reproduction, where the breeder crosses two parents, each carrying desirable traits (F1), and then selects from the offspring the individuals that combine the greatest number of these traits (F2, F3, etc.). The main advantage of this method is that it does not require prior knowledge of the genes responsible for the desired traits, as selection is based only on the phenotype (17).

As for the constraints, they include:

✓ The length of time required, as developing a new variety takes 8 - 12 years, due to the need for several generations of backcrossing to eliminate undesirable traits associated with the desired trait.

✓ Limiting crossbreeding to sexually compatible species, which prevents the introduction of traits from genetically distant organisms.

✓ The difficulty of improving complex, multi-gene traits because the effect of each gene individually is small and difficult to track across generations.

✓ The phenomenon of harmful genetic linkage, where undesirable genes are transferred along with the target gene, requiring additional generations to separate them (18,19).

2. Induced mutations:- In this method, seeds or plant tissues are exposed to chemicals or radiation to cause random genetic mutations, and plants that show improved traits are selected. This method has contributed to the production of thousands of improved varieties of wheat, rice, and barley (20). The technique of induced mutations relies on increasing the rate of spontaneous mutations in plants using physical mutagens such as gamma rays, X-rays, fast neutrons (21), or chemical mutagens such as ethyl methanesulfonate EMS. (22). These mutations occur randomly throughout the genome, and the breeder then examines thousands of treated plants to find individuals carrying desirable, improved traits. Among the most notable achievements of this technique are the production of wheat varieties with shorter stalks, which reduces lodging, the production of barley varieties with high protein content, and early-maturing rice varieties. More than 3,200 improved plant varieties have been produced worldwide using this technique (20).

As for the limitations, they include:

✓ Complete randomness, as it is impossible to control the location or type of mutation (23).

✓ The need to examine enormous numbers of plants (often tens of thousands) to find a single beneficial mutation, because most mutations are either neutral or harmful (24).

✓ A long time is required to fix the mutation and to ensure its genetic stability across several generations (23).

✓ Difficulty in distinguishing the mutant variety from the original variety without molecular techniques (25).

3. Genetic engineering (genetic modification):- This technique is considered one of the most precise and effective techniques, as it allows the transfer of a specific gene from one organism to another (even if it is between sexually incompatible species) in order to acquire a specific trait (26), For example, varieties of cotton and corn resistant to insects have been produced by introducing genes from the bacterium *Bacillus thuringiensis*. Crops resistant to herbicides have also been produced, which facilitates the control process and reduces competition for resources (27). Genetic engineering relies on introducing a foreign gene from another living organism (bacteria, fungus, another plant, another animal) into the plant genome with the aim of acquiring a trait not originally present in the plant or enhancing an existing trait (28). With the rapid development of life technology systems, it has become easy to induce genetic variation in many plant species using some of them (29): -

✓ Infection with Agrobacterium bacteria, Agrobacterium-mediated transformation.

✓ Fine microinjection.

✓ Using protoplasts: Protoplast transformation.

✓ Gene biolistics Gene gun.

One of the most prominent successful applications is insect-resistant crops that produce proteins toxic to the larvae of certain insects but are safe for humans and mammals, which has reduced the use of Insecticides by up to 37% in genetically modified crops (30). Additionally, genetically enhancing the nutritional value to produce beta-carotene (a substance that converts to vitamin A in the body) addresses vitamin A deficiency, which causes blindness in developing countries (31).

Some of the advantages of this technology:

✓ Overcoming sexual compatibility barriers, allowing the transfer of genes from any living organism (32).

✓ Relative speed compared to traditional breeding (33).

✓ Accuracy in transferring a specific single gene without unwanted linked genes (34).

As for the restrictions, they include: -

✓ Regulatory and social concerns in many countries where legislation varies significantly between countries (35).

✓ The need to conduct prolonged safety tests before marketing (36).

✓ The possibility of eliciting negative public reactions among some consumers (37).

4. Gene Editing Techniques (CRISPR-Cas9):-

This represents the latest revolution in this field, and this technique allows for precise modification of genes present in plants, similar to a 'molecular scissors,' where a specific part of the DNA can be cut to disable an undesired gene or repair another gene to enhance a positive trait (38). This technology is characterized by the fact that it does not introduce foreign genes from other organisms, which makes its results closer to natural mutations that occur in nature, but in a faster and more targeted way (39). The CRISPR-Cas9 technology first appeared in 2012 as a system found in the bacterium *Streptococcus pyogenes*, serving as a natural immune system that fights viruses, and then it was developed to become a precise tool for gene editing (40). The system relies on two main components that work together as a 'navigation and precision surgery' system. The first is the Cas9 enzyme, which acts as a molecular pair of scissors whose job is to cut DNA strands at a specific site. The second is a guide RNA molecule (sgRNA), which consists of 20 nucleotides at its end and can be designed in the lab to match any desired genetic sequence, guiding the Cas9 enzyme to that site with high precision, once the target site is found (provided there is a PAM signal next to it) (41). This technology was developed to include advanced versions that surpass the capabilities of the first generation without cutting the DNA strand. It is very useful for correcting nitrogenous bases from one to another, such as converting the adenine base to guanine (A to G) or converting the thymine base to cytosine (T to C), and it allows for the insertion, deletion, or replacement of any genetic sequence up to 44 nitrogenous bases (42).

Some of the most prominent features of this technology compared to traditional genetic engineering are: -

✓ It does not leave any foreign DNA in the plant, as the temporary DNA used in editing can be removed after the process is completed (43).

✓ Extremely high precision, reaching a single nucleotide (44).

✓ High speed, as improved plants can be obtained in very few generations (45).

✓ From a regulatory perspective, the results of genetic editing do not contain foreign DNA and are closer to natural mutations, which has led to their exemption from the strict regulations on genetically modified organisms in several countries, including the United States, Japan, and the United Kingdom (46).

As for the limitations, they include:

✓ Unintended effects on the genome and the possibility of modifications occurring at unintended sites, although modern design improvements have significantly reduced these risks (47)

✓ Difficulty in delivering the editing components to certain types of plants and cells, which complicates precise editing processes that require Homology-Directed Repair (HDR) in plants (48).

✓ Low efficiency in the mechanism of introducing new sequences (47).

Applications in Facing Environmental Challenges

Through these techniques, scientists have been able to achieve tangible accomplishments in improving the ability of crops to adapt to harsh environmental conditions, which are represented in the following: -

1. **Drought tolerance**: Varieties of maize and wheat have been developed containing genes that enable them to close leaf stomata more efficiently during periods of drought or to develop deep roots that reach groundwater (49). Some genetically modified varieties are capable of maintaining their productivity even with a reduction in irrigation levels of up to 25% (50).
2. **Salt tolerance:** Soil salinity is considered one of the greatest obstacles in arid and semi-arid regions by introducing genes responsible for regulating toxic ions such as sodium ions and chloride ions within the plant cell (51), and varieties of rice and tomatoes capable of growing and fruiting in saline soil that was previously considered unsuitable have been produced (52).
3. **Resistance to thermal changes:** With the rise in global temperatures, varieties of soybean and wheat have been improved to withstand heat waves during the flowering period, which is the most sensitive stage, ensuring that the yield does not decrease significantly (53).
4. **Pest and disease resistance:** To reduce the use of chemical pesticides, pest-resistant crops help protect the environment and reduce costs for the farmer, as well as decrease greenhouse gas emissions associated with the manufacturing and application of pesticides (54).

Future prospects

With the rapid development of molecular biology tools, applications are no longer limited to major strategic crops such as wheat, barley, rice, and corn, but have begun to extend to crops that receive less research attention (food security crops for the poor), such as millet and sweet potato (55,56). There is also an increasing trend towards improving more complex traits that were previously considered beyond the reach of conventional breeding, such as photosynthetic efficiency, the ability to fix atmospheric nitrogen in non-leguminous crops, and tolerance to multiple simultaneous stresses instead of just one stress (57,58). Nevertheless, there remain real challenges facing this field, including: -

Organizational and legal challenge: - The laws of many countries still lag behind technological advancement, as they confuse traditional genetic engineering with precise gene editing techniques, which hinders the implementation of solutions that could be safer than the conventional varieties themselves (59).

The economic challenge: - The cost of developing an improved variety using modern technologies remains high, making it exclusive to large companies and crops with high economic returns, while neglecting the crops grown by the poor in the most needy areas (60).

Social challenge: - There are still legitimate concerns among some consumers and farmers about genetically modified crops. Some of these concerns stem from a lack of information, while others arise from past bad experiences with monopolistic companies or irresponsible practices. This requires a transparent and continuous dialogue with the public (61).

Conclusion

It can be said that improving genetic traits has become an urgent necessity in an era where climate change is accelerating, the population is increasing, and the per capita share of land and water is decreasing. However, its success depends on the ability of the scientific community, policymakers, farmers, and consumers to work together not only to develop better technologies but also to ensure that these technologies reach those who need them and in a way that respects the environmental, social, and economic diversity of different regions of the world.

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