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Editorial note

A critical perspective on gene editing in modern agriculture

Una perspectiva crítica sobre la edición genética en la agricultura moderna

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ABSTRACT

Gene editing technologies have emerged as some of the most transformative tools in modern agricultural science. Over the past decade, the refinement of clustered regularly interspaced short palindromic repeats (CRISPR) and associated protein systems, alongside earlier platforms such as zinc-finger nucleases (ZFNs) and transcription activator-like effector nucleases (TALENs), has altered what is possible in crop improvement and sustainable food production. This note examines the scientific foundations of agricultural gene editing, surveys the breadth of its current applications, evaluates its agronomic and environmental implications, addresses regulatory and ethical considerations, and reflects on the trajectory of this field as it confronts the urgent challenges of feeding a growing global population in an era of accelerating climate change.

Keywords: abiotic stress tolerance, agronomic performance, disease resistance, herbicide and pest tolerance, nutritional quality

RESUMEN

Las tecnologías de edición genética se han consolidado como algunas de las herramientas más transformadoras de la ciencia agrícola moderna. Durante la última década, el perfeccionamiento de las repeticiones palindrómicas cortas agrupadas y espaciadas regularmente (CRISPR) y los sistemas de proteínas asociados, junto con plataformas anteriores como las nucleasas con dedos de zinc (ZFN) y las nucleasas efectoras tipo activador de la transcripción (TALEN), ha modificado las posibilidades en la mejora de cultivos y la producción sostenible de alimentos. Esta nota examina los fundamentos científicos de la edición genética agrícola, analiza la amplitud de sus aplicaciones actuales, evalúa sus implicaciones agronómicas y ambientales, aborda las consideraciones regulatorias y éticas, y reflexiona sobre la trayectoria de este campo ante los urgentes desafíos para alimentar a una población mundial en crecimiento, en una era de cambio climático acelerado.

Palabras clave: calidad nutricional, rendimiento agronómico, resistencia a enfermedades, tolerancia al estrés abiótico, tolerancia a herbicidas y plagas

Introduction

Classical plant breeding often requires many years of crossing and selection to stabilize desirable traits. Conventional transgenic approaches accelerated crop improvement but introduced limitations associated with random insertion of foreign DNA and concerns regarding genomic unpredictability and horizontal gene transfer. In contrast, gene-editing technologies enable precise and predictable modifications at specific genomic loci, including gene knockouts, nucleotide substitutions, and targeted sequence insertions, without incorporating foreign genetic material (Chen *et al*., 2019; Gao, 2021). The importance of these technologies is amplified by growing global food security challenges. The Food and Agriculture Organization projects that food demand will increase by 50% by 2050 due to population growth and changing dietary patterns (FAO, 2021). Simultaneously, climate change is expected to reduce crop productivity through increased drought, heat stress, and emerging pathogens. In this context, gene editing represents a promising strategy to accelerate crop improvement and enhance agricultural resilience, thereby contributing to sustainable food production systems (Gao, 2021).

From ZFNs and TALENs to CRISPR

Modern gene-editing technologies originated with zinc-finger nucleases (ZFNs), engineered proteins that combine DNA-binding zinc-finger domains with the FokI endonuclease to induce targeted double-strand DNA breaks. Although effective, ZFNs were technically complex and costly because each target sequence required the design of a new protein. Transcription activator-like effector nucleases (TALENs), introduced around 2010, provided a more modular and flexible alternative and were widely adopted in plant research. TALEN-based approaches enabled targeted modifications in crops such as maize, wheat, and rice, including the development of disease-resistant rice through editing of *OsSWEET* susceptibility genes (Li *et al*., 2012). The emergence of the CRISPR-Cas9 system represented a breakthrough in genome editing (Doudna & Charpentier, 2012). Unlike ZFNs and TALENs, CRISPR-Cas9 uses a short guide RNA (gRNA) to direct the Cas9 nuclease to specific genomic targets, eliminating the need for extensive protein engineering. This innovation reduced the cost, complexity, and time required for genome editing, greatly expanding its accessibility for plant research and breeding. Furthermore, the successful delivery of CRISPR components through *Agrobacterium tumefaciens* in major crops such as maize has facilitated the broad application of this technology in agricultural biotechnology (Char *et al.,* 2017).

Applications in crop improvement

Disease resistance. Plant diseases are responsible for substantial annual crop losses worldwide. Gene editing has been used to improve resistance by disrupting host susceptibility (*S*) genes exploited by pathogens during infection (Sedeek *et al*., 2019). One of the most studied examples involves the *MLO* gene family in cereals. Functional *MLO* proteins are required for powdery mildew infection, and CRISPR-Cas9-mediated disruption of MLO genes in wheat, barley, and tomato has produced durable resistance without significant yield penalties (Chen *et al*., 2019). Gene editing has also improved resistance to bacterial diseases. In citrus, *Xanthomonas citri*, the causal agent of citrus canker, activates host *SWEET* genes to redirect sugars toward infection sites. Editing of the *SWEET* promoter in sweet orange reduced susceptibility to canker (Gao, 2021). Similarly, editing of *TaEDR1* in wheat and *OsSWEET14* in rice enhanced resistance to powdery mildew and bacterial blight, respectively.

Abiotic stress tolerance. Climate change is increasing the frequency and intensity of drought, salinity, and heat stress, thereby threatening agricultural productivity worldwide (FAO, 2021). Gene editing has been used to enhance crop resilience to these environmental stresses. Drought tolerance has been improved through the modifications of genes associated with stomatal regulation, root architecture, and stress signaling pathways. For example, edited *SlMAPK3* tomato plants exhibited enhanced drought tolerance and reduced oxidative stress. In maize, modification of the *ARGOS8* gene improved yield stability under water-limited conditions (Gao, 2021). In rice, editing of genes such as *OsDERF1* and *OsPMS3* produced lines with improved tolerance to drought and salinity (Chen *et al*., 2019). Heat stress is important in wheat and other cool-season crops. Gene editing of heat-responsive regulatory pathways, including the *HSP90* chaperone network, is being explored to improve thermotolerance. Base-editing approaches have also accelerated the transfer of favorable alleles from heat-tolerant wild relatives into elite cultivars (Molla *et al*., 2021).

Yield and agronomic performance. Improving crop productivity remains a central objective in agriculture. Gene editing has demonstrated potential to increase yield through modifications of genes controlling grain size, fruit development, and plant architecture. In tomato, CRISPR-mediated editing of genes such as *CLV3* improved fruit size, branching, and ripening. Editing of cis-regulatory elements allowed fine-tuning of gene expression, mimicking dosage effects achieved through long-term breeding (Gao, 2021). In rice, modifications of *GN1a*, *GW5*, and *GS3* increased grain size and yield. Similarly, editing of *TaGW2* in wheat produced plants with heavier grains across multiple genetic backgrounds (Chen *et al*., 2019). Plant architecture has also been targeted through the editing of semi-dwarfing genes such as *Rht* in wheat and sd1 in rice. These genes reduce gibberellin activity, generating shorter, lodging-resistant plants capable of supporting higher grain loads.

Nutritional quality. Gene editing has expanded opportunities to improve the nutritional composition of staple crops (Zhu *et al*., 2019). One of the most advanced applications involves soybean oil quality. CRISPR-mediated editing of *FAD2* and *FAD3* genes generated high-oleic soybean varieties with improved oil stability and reduced trans-fat formation (Waltz, 2018). Genome editing has also been used to reduce anti-nutritional compounds. Phytic acid, which limits mineral bioavailability and contributes to phosphorus pollution, has been reduced in maize and rice through the editing of genes involved in its biosynthesis (Zhu *et al*., 2019). Additional studies aim to reduce allergenic proteins in peanut and wheat and to decrease trypsin inhibitors in cowpea (Sedeek *et al*., 2019). Biofortification represents another major application. Editing of endogenous pathways regulating provitamin A, iron, zinc, and folate accumulation has been explored to improve micronutrient content in staple crops without introducing foreign DNA.

Herbicide and pest tolerance. Gene editing has also facilitated the development of herbicide-tolerant crops. Instead of inserting foreign genes, CRISPR can modify endogenous genes encoding herbicide-target enzymes. Mutations in the acetolactate synthase (*ALS*) gene confer tolerance to imidazolinone and sulfonylurea herbicides and have been introduced into crops such as rice, wheat, flax, and watermelon (Waltz, 2018). Pest management applications are also advancing. In cotton, editing of gossypol biosynthesis genes aims to reduce seed toxicity while maintaining insect resistance in leaves. In potato, editing of *StVIF2* reduced cold-induced sweetening and acrylamide formation during frying, while additional modifications targeting late blight susceptibility genes have improved resistance to one of the crop's most destructive diseases (Gao, 2021).

Ethical considerations

Agricultural gene editing raises ethical concerns that extend beyond biosafety and regulatory considerations. Public debate frequently centers on the concept of "naturalness," reflecting societal values regarding human intervention in biological systems and food production. Although conventional breeding methods also involve extensive genetic manipulation, including induced mutations and wide hybridization, concerns regarding the integrity of natural systems remain significant and warrant careful consideration rather than dismissal (Rothschild, 2020). Another major concern involves the concentration of market power within the seed and agrochemical industries. The high costs associated with the development and commercialization of gene-edited crops tend to favor multinational corporations over public institutions and small-scale breeders. Critics argue that, similar to previous agricultural biotechnologies, gene editing could further consolidate control over seed systems, thereby reducing farmer autonomy and agricultural biodiversity (Chen *et al*., 2019). These concerns have stimulated support for open-access gene-editing technologies, increased public investment in crop improvement programs, and regulatory frameworks that promote equitable participation in agricultural innovation. International research organizations, national agricultural research systems, and university breeding programs play a critical role in ensuring that the benefits of gene editing are distributed more broadly and are not limited to private commercial interests (FAO, 2021).

Future directions

Gene-editing technologies are advancing rapidly, increasing the precision and efficiency of crop improvement. Prime editing enables targeted point mutations and small insertions or deletions without inducing double-strand DNA breaks, thereby offering highly precise genome modification across multiple crop species (Anzalone *et al.*, 2020; Molla *et al.*, 2021). Epigenome editing further expands these possibilities by modifying DNA methylation and histone patterns without altering the nucleotide sequence, thereby allowing reversible regulation of gene expression. The integration of gene editing with genomic selection is accelerating breeding programs by enabling the rapid incorporation of favorable alleles into elite cultivars while shortening breeding cycles. Artificial intelligence and machine learning are also being applied to identify optimal editing targets and predict off-target effects in complex genomes (Gao, 2021). In addition, gene editing is converging with synthetic biology to redesign plant metabolic pathways. Major long-term objectives include engineering nitrogen fixation in cereals, improving photosynthetic efficiency, and producing pharmaceutical compounds or industrial feedstocks in crops (Zhu *et al.*, 2019; Gao, 2021).

Conclusion

Gene editing has advanced agricultural biotechnology by enabling precise, efficient, and versatile modification of crop genomes. Applications such as disease-resistant wheat, drought-tolerant maize, and high-oleic soybeans demonstrate the potential of this technology to improve agricultural productivity, sustainability, and food quality. Progress in CRISPR-based technologies, delivery systems, computational biology, and screening methods continues to accelerate the development of improved agricultural varieties. Despite these benefits, the responsible application of gene editing requires careful consideration of regulatory, ecological, and social challenges. Effective regulatory frameworks must ensure biosafety while avoiding barriers that may restrict participation by public-sector institutions and researchers in developing countries. Equitable access to gene-editing technologies also depends on balanced intellectual property policies that promote broader availability of these tools. Furthermore, potential ecological impacts and interactions with natural ecosystems require comprehensive risk assessment. Public engagement remains essential for addressing societal concerns regarding sustainability, food systems, and technological governance. Although not a universal solution, gene editing represents a powerful tool for improving food security, agricultural resilience, and sustainable production systems.

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