

Current Status of Research, Regulations, and Future Challenges for CRISPR Gene Editing in Crop Improvement¹

Sadikshya Sharma, Kaitlyn Vondracek, Heqiang Huo, Tie Liu and Seonghee Lee²

Introduction

Plant breeders and researchers have sought to improve crops since the dawn of agriculture. For hundreds of years, conventional breeding has had a tremendous impact on agricultural productivity. Over the last few decades, researchers have begun to transfer DNA between species in what is known as genetic engineering (transgenic technology). Recently, new plant-breeding technology such as CRISPR gene editing has provided the potential to substantially improve crop breeding in agriculture. Considerable efforts have been devoted to applying this gene-editing technology in modern agriculture to increase crop yields and improve the quality of food ingredients, especially by many of the major agronomic seed-producing companies. In this article, we outline the recent research updates and regulations on gene editing in crop improvement. The target audience for this report is the general public, including both scientists and nonscientists.

What is CRISPR and how does it work?

CRISPR, or clustered regularly interspaced short palindromic repeats, is a gene-editing technology derived from a bacterial defense mechanism. This defense mechanism

works in three phases (figure 1). Phase 1, or Adaptation, occurs when a bacteriophage (or other type of invader) infects bacteria by a small amount of DNA into the cell (Vigouroux & Bikard, 2020).

During Adaptation, short fragments of the injected DNA are 'saved' by the bacteria within a repetitive region of the genome, referred to as a CRISPR array (Vigouroux & Bikard, 2020). Each array consists of a unique spacer derived from these short fragments interspaced between repeats. The CRISPR locus is then transcribed and processed during Phase 2, resulting in short RNA sequences corresponding to the sequences of the invading DNA fragments (Vigouroux & Bikard, 2020). The RNAs processed during Phase 2 are then used in Phase 3, Interference, for Cas nucleases to create double stranded breaks (DSBs) in the invading DNA (Vigouroux & Bikard, 2020). Bacteria are protected from DNA damage because the Cas nucleases requires a proto-spacer adjacent motif (PAM) site immediately adjacent to the recognized sequence (Doudna & Charpentier, 2014), which is not present in the bacteria.

CRISPR/Cas-mediated gene editing technology takes advantage of this naturally occurring defense mechanism by synthetically adding sequences, referred to as guide RNAs (gRNAs), into a CRISPR locus. These sequences

1. This document is HS1334, one of a series of the Horticultural Sciences Department, UF/IFAS Extension. Original publication date August 2019. Revised August 2023. Visit the EDIS website at <https://edis.ifas.ufl.edu> for the currently supported version of this publication.
2. Sadikshya Sharma, OPS, UF/IFAS Gulf Coast Research and Education Center; Heqiang Huo, assistant professor, Environmental Horticulture Department, UF/IFAS Mid-Florida REC; Kaitlyn Vondracek, Graduate Assistant, UF/IFAS GCREC; Tie Liu, Assistant Professor, Horticultural Sciences Department; and Seonghee Lee, associate professor, Horticultural Sciences Department, UF/IFAS GCREC; UF/IFAS Extension, Gainesville, FL 32611.

The Institute of Food and Agricultural Sciences (IFAS) is an Equal Opportunity Institution authorized to provide research, educational information and other services only to individuals and institutions that function with non-discrimination with respect to race, creed, color, religion, age, disability, sex, sexual orientation, marital status, national origin, political opinions or affiliations. For more information on obtaining other UF/IFAS Extension publications, contact your county's UF/IFAS Extension office. U.S. Department of Agriculture, UF/IFAS Extension Service, University of Florida, IFAS, Florida A & M University Cooperative Extension Program, and Boards of County Commissioners Cooperating. Andra Johnson, dean for UF/IFAS Extension.

are typically 20 nucleotides long and are found and analyzed using various available software. Cas9 is one of the most common Cas nucleases used in gene editing. Cas9 recognizes a 3 nucleotide PAM sequence, 5'-NGG-3', where N represents any nucleotide. Variations of Cas nucleases have been engineered to require different PAM sequences, allowing for greater flexibility in gene editing application. Once the gRNAs are added into a CRISPR vector, plant tissue is transformed using one of many methods. Agrobacterium-mediated transformation and biolistic transformation via the use of a gene gun are two of the more common transformation methods, though new methods are continuously being developed for improved editing efficiency and transgene-free applications. Once transformation is complete, the CRISPR/Cas system will function in a similar manner as in bacteria. The guide sequences will be transcribed and processed into gRNAs, which will match up to regions in the host genome. If the correct PAM site is present adjacent to the matching host sequences, the selected Cas nuclease will be recruited to generate a DSB at that position. If the correct PAM site is not present, Cas will not cut the DNA at that position, and the complex will move to the next matching site.

Mutations in CRISPR gene editing arise from the DNA repair mechanisms for DSBs. There are two systems for DSB repair in eukaryotes, non-homologous end-joining (NHEJ) and homology-directed repair (HDR). Homology directed repair utilizes a template, either the sister chromatid of the target chromosome or an externally supplied one, to repair the break in the DNA. Using HDR, one can generate a precise insertion or modification by including the desired sequence as the template. Conversely, NHEJ occurs in the absence of a template, and instead relies on an error-prone repair mechanism, resulting in a random insertion or deletion at the position of the break. It is also possible that no error occurs during repair, in which case the host DNA will be indistinguishable from before it was cut.

How does CRISPR gene-editing technology improve crops and benefit the public?

Using the CRISPR gene-editing technique, researchers can selectively “edit” plant genomes to obtain desired traits.

Gene editing is occasionally confused with the transgenic approach (colloquially referred to as “GMO”) and referred to as the same idea. Schneider et al. (2014) describe clearly what genetically modified (GM) foods or genetically modified organisms (GMO) are as well as other possible

benefits of crop improvement. In other EDIS articles (Lee et al. 2016, 2018), we have also described what gene-editing techniques are, how they differ from transgenic approaches, and their potential applications for cultivated strawberries. CRISPR gene-editing technology has been applied to various crops to increase yield, disease resistance, and nutritional quality. These crops include wheat, tomato, banana, rice, cassava, cucumber, grape, apple, citrus, canola, and corn. For example, to increase yield, tomatoes with double the number of branches were created by Lippman and colleagues at Cold Spring Harbor Laboratory (Rodríguez-Leal et al. 2017; Rothan et al. 2019). Besides yield, gene editing in tomatoes can create enhanced nutritional quality and biotic and abiotic stress resistance, which would otherwise take decades to achieve through traditional breeding (Krishna et al. 2019). Huanglongbing (HLB), or citrus greening, is a devastating disease of citrus worldwide, and in Florida it has reduced citrus production by more than 50%. There is currently no genetic resistance source available for HLB-resistance breeding (Khachatryan and Choi 2017; Dodds, Gorham, and Rumble, 2017; Ledford 2017), but Dr. Nian Wang’s group at UF/IFAS has begun to generate greening-resistant citrus varieties using CRISPR-based gene editing, which could potentially save the Florida citrus industry.

Some important quality concerns in various foods can also be improved using gene-editing technology. For example, reduced-gluten wheat, nonbrowning mushrooms and apples, and soybeans with reduced unhealthy saturated fats can be obtained using CRISPR gene-editing tools (Waltz, 2016; Jacobs et al. 2015; Sánchez-León, et al. 2017). Table 1 lists the agricultural companies that are currently using CRISPR gene-editing techniques to improve crops.

What CRISPR gene-edited foods are available in grocery stores?

Gene-edited soybean oil, cold-storable potatoes, high-fiber and gluten-reduced wheat, and lower-saturated-fat canola have been developed by Calyxt (formerly Collectis Plant Sciences, Inc., New Brighton, MN), *Calyxt’s gene-edited soybean oil was cleared by the USDA in 2018 and went on the US market in 2019, and while their high-fiber wheat was cleared by the USDA in 2018, it was not commercialized. In 2018, the USDA also cleared Gene- the EPA will not regulate edited camelina with increased oil content from Yield10 Bioscience, which is now in pre-commercial seed production. Starting in 2019, Cibus began cultivating gene-edited herbicide resistant canola (SU Canola + Draft herbicide growing system) in North Dakota and Montana. USDA-APHIS*

cleared herbicide tolerant flax and rice from Cibus in 2020, and waxy corn from Corteva in 2021. Pairwise intends to release gene-edited high-nutrient romaine and low-pungency mustard greens for commercial sale in 2023 and is additionally working on gene-editing in strawberry, blackberry, and raspberry. Gene-edited crops are also becoming more widely available in the global market. In 2020, Japan's regulatory agencies approved gene-edited tomatoes with increased γ -aminobutyric acid (also known as GABA) content, and Alora, a Canada-based startup, has secured permission for field trials of salt-tolerant gene-edited rice in Vietnam and Kenya starting in 2023. In 2022, Argentina's Biosafety Commission (Comisión Nacional de Biotecnología Agropecuaria or "CONABIA") cleared Yield10 Bioscience's gene-edited camelina, and Japan's Ministry of Health, Labour, and Welfare (MHLW) and Ministry of Agriculture, Forestry, and Fisheries (MAFF) cleared Corteva's waxy gene-edited corn in 2023.

Current Regulations and Policies for CRISPR Gene-Edited Crops

With the advent of recombinant DNA in the 1980s, the Coordinated Framework for Regulation of Biotechnology was issued by the White House Office of Science and Technology Policy. In the United States, three Federal agencies, the Environmental Protection Agency (EPA), the United States Department of Agriculture (USDA), and the Food and Drug Administration (FDA), were charged with the implementation of laws regulating biotechnology products (Food and Drug Administration, 2023). The EPA mainly regulates bioengineered products intended for pesticidal purposes, biofertilizers, bioremediation, and the production of various industrial compounds, including biofuels. As such, the EPA will not regulate

CRISPR-edited plants as long as the altered traits are not for synthesis of toxic chemicals such as pesticides or biofuels. Similarly, the FDA focuses on the safe regulation of genetically engineered foods that can be used for dietary supplements, cosmetics, drugs, and medical devices. The FDA ensures food products comply with legal requirements, regardless of their production methods (whether traditional or gene-edited). The USDA's Animal and Plant Health Inspection Service (USDA-APHIS) authorizes the importation, interstate movement, and environmental release of plants that may pose a plant pest risk. Regulation of genetically modified and gene edited crops by USDA-APHIS began in 1987 under the Coordinated Framework for Regulation of Biotechnology, 7 CFR part 340 (United States Department of Agriculture, 2022). Further revisions

to APHIS's regulatory policy were made in May of 2020 and included several changes to the existing system.

Research on the CRISPR-Cas9 system for gene editing is performed worldwide, but there is still no internationally agreed-upon regulatory policy for gene-edited products. In the United States, the FDA, EPA, and USDA-APHIS have taken different steps toward regulating agricultural products produced by new plant-breeding technologies, including CRISPR gene editing. The FDA has no additional requirement for the food safety assessment of gene-edited crops. However, the FDA will regulate gene-editing used in animals as "new animal drugs."

On May 24, 2023 the EPA announced a final rule for an exemption proposed in October of 2020 regarding regulation of plant-incorporated protectants (PIPs) (Environmental Protection Agency, 2023; Mendelsohn et al, 2023; Stockstad, 2023), PIPs are pesticidal substances which are produced in and used in and used by plant as pesticide (Mendelsohn et al., 2023). The 2023 final rule reflects advancements made in biotechnology since 2001, when PIPs derived from conventional breeding were exempted from regulation while maintaining regulatory requirements for PIPs produced through biotechnology (Environmental Protection Agency, 2023). Under the final rule, gene-edited plants will be exempt from the in-depth review process if the introduced trait already exists within the plant's gene pool and if data is submitted indicating the gene-edited plant won't harm the plant's ecosystem or cause harm to consumers (Stokstad, 2023). This regulatory change comes as a result of significant advancements in biotechnology which enable the creation of PIPs through gene-editing and genetic engineering that are virtually indistinguishable from those produced using traditional breeding methods (Environmental Protection Agency, 2023). On March 28, 2018, USDA Secretary of Agriculture, Sonny Perdue, issued a formal statement on innovative plant-breeding techniques (including CRISPR gene editing), explaining that the USDA does not have plans to evaluate gene-edited plants for health and environmental safety if they could otherwise have been developed through traditional breeding, unless these gene-edited plants are potential plant pests or developed using plant pests (United States Department of Agriculture, 2018). The 2020 revisions to F CFR 340 provide a more in-depth definition for plants eligible for non-regulated status (United States Department of Agriculture, 2020(b)). Under these updates, regulations do not apply to organisms which contain one of the following modifications: cellular repair of targeted double-stranded break in absence of externally provided template (7 CFR 340.1(b)(1)), targeted single base

pair substitution (7 CFR 340.1(b)(2)), or introduction of a gene known to occur within the plant's gene pool, change of target sequence to match a known allele within the plant's gene pool, or targeted changes to correspond to a known structural variant in the plant's gene pool (7 CFR 340.1(b)(3)). A plant can additionally be considered non-regulated following submission of exemption proposals by either USDA-APHIS or an external party if the resulting modification(s) could be achieved through conventional breeding (7 CFR 340.1(b)(4)(i) and 7 CFR 340.1 (b)(4)(ii)). On May 14, 2020, USDA Secretary of Agriculture, Sonny Perdue, announced a press release revealing a final rule to update USDA regulations of biotechnology under the plant protection act (United States Department of Agriculture, 2020(a)). This final rule, titled the Sustainable, Ecological, Consistent, Uniform, Responsible, Efficient (SECURE) rule, will enable more efficient and effective regulatory oversight by focusing on risks posed by traits introduced during gene-editing rather than whether the gene-edited plant was developed using a plant pest (Hoffman, 2021; United States Department of Agriculture, 2020(a)). The SECURE rule additionally includes a mechanism for rapid initial review to identify and separate plants which do not plausibly increase plant pest risk from those that do (Hoffman, 2021). Plants which are identified to plausibly increase plant pest risk will be subject to further regulation.

In contrast to the United States, the European Court of Justice has ruled that gene-editing techniques fall within the European Union's 2001 GMO directive, meaning that gene-edited products should be treated like traditional transgenic products (Faure and Napier 2018) and be subjected to a mandatory risk assessment (Callaway 2018). According to Faure and Napier, CRISPR gene-editing technology will not be profitable in the European Union and is unlikely to be implemented soon.

Several scientists in Europe together with the European Commission's top scientific advisory panel have sharply rebuked both the European Court decision on gene editing and Europe's entire framework for regulating genetically modified organisms (Conrow, 2018; Pothering, 2019). Gene editing is also currently considered GM in New Zealand and controlled by the Environmental Protection Authority (EPA). While gene-edited crops are still heavily regulated globally, several countries have started loosening restrictions on edited crops, including India (Government of India Ministry of Science & Technology Department of Biotechnology, 2022), Argentina, Brazil, Chile, Colombia, Paraguay, Israel, Japan, and Australia (Menz et al., 2020). While the EU and New Zealand have yet to loosen

restrictions for gene-edited crops, there are calls for updates to the regulatory systems based on decades of regulatory experience and consumer studies (Dayé et al., 2023; Van Der Meer et al., 2023; Voigt, 2023).

Conclusion

Gene-editing techniques like CRISPR and TALEN are fundamental breakthroughs in plant genetic improvement that can adjust desired traits more quickly and precisely than traditional breeding. In recent years, gene editing has been applied in many crop systems to improve important agronomic traits such as yield, nutritional value, and disease resistance. However, there still seems to be widespread public concern and regulatory uncertainty over food ingredients from gene-edited crops. Nevertheless, such foods will soon be available on supermarket shelves, and therefore it is important that the regulatory status of gene-edited foods is clarified and that consumers are adequately informed about the new technology.

References

- Callaway, E. 2018. "CRISPR plants now subject to tough GM laws in European Union." *Nature* 560(7716): 16.
- Conrow, J. (2018, November 14). Top science panel criticizes EU's GMO regulations. Alliance for Science. <https://allianceforscience.org/blog/2018/11/%20top-science-panel-criticizes-eus-gmo-regulations/>
- Dayé, C, Spök, Allan, A. C., Yamaguchi, T., & Spink, T. (2023). *Social Acceptability of Cisgenic plants: Public Perception, Consumer Preference, and Legal Regulations* (pp. 43-75). http://doi.org/10.1007/978-3-031-10721-4_3
- Dodds, N. M. W., L. M. Gorham, and J. N. Rumble. 2017. *Floridians' Perceptions of GMOs: GMOs and Florida Citrus*. AEC520. Gainesville: University of Florida Institute of Food and Agricultural Sciences. <https://edis.ifas.ufl.edu/wc182>
- Doudna, J. A., & Charpentier, E. (2014). *The new frontier of genome engineering with CRISPR-cas9*. <https://www.science.org>
- Environmental Protection Agency (2023). *Pesticide; Exemptions of Certain Plant-Incorporated Protectants (PIPs) Derived from Newer Technologies*. (FRL No. 7261-04-0CSPP).
- Faure, J-D., and J. A. Napier. 2018. "Europe's first and last field trial of gene-edited plants?" *eLife* 7: e42379.

- Food and Drug Administration. (2023, April 13). *New Plant Variety Regulatory information*. U.S. Food and Drug Administration. <https://www.fda.gov/food/food-new-plant-varieties/new-plant-variety-regulatory-information#:~:text=The%20FDA%20regulates%20human%20and.sold%20in%20the%20the%20United%20states>
- Government of India Ministry of Science & Technology Department of Biotechnology. (2022). Standard Operating Procedures for Regulatory Review of Genome Edited Plant under SDN-1 and SDN-2 Categories.
- Hoffman, N. E. (2021). Revisions to USDA biotechnology regulations: The SECURE rule. *Proceeding of the National Academy of Sciences of the United States of America*, 118(22). <http://doi.org/10.1073/pnas.2004841118>
- Jacobs, T. B., et al. 2015. "Targeted genome modifications in soybean with CRISPR/Cas9." *BMC Biotechnology* 15: 16.
- Khachatryan, H., and H. J. Choi. 2017. *Factors Affecting Consumer Preferences and Demand for Ornamental Plants*. FE938. Gainesville: University of Florida Institute of Food and Agricultural Sciences. <https://edis.ifas.ufl.edu/fe938>
- Krishna, R., et al. 2019. "Transgenic tomatoes for abiotic stress tolerance: status and way ahead." *3 Biotech* 9:143.
- Ledford, H. 2017. "Engineered virus in line to battle citrus disease." *Nature* 545: 277.
- Lee, S., Y-H. Noh, S. Verma, and V. M. Whitaker. 2016. *DNA, Technology, and Florida Strawberries*. HS1287. Gainesville: University of Florida Institute of Food and Agricultural Sciences. <https://edis.ifas.ufl.edu/hs1287>
- Lee, S., C. Yoo, K. Folta, and V. M. Whitaker. 2018. *CRISPR Gene Editing in Strawberry*. HS1315. Gainesville: University of Florida Institute of Food and Agricultural Sciences. <https://edis.ifas.ufl.edu/hs1315>
- Mendelsohn, M., Pierce, A. A., & Striegel, W. (2023). U.S. EPA oversight of pesticide traits in genetically modified plants and recent biotechnology innovation efforts. In *Frontiers in Plant Science* (Vol. 14). Frontiers Media S.A. <https://doi.org/10.3389/fpls.2023.1126006>
- Menz, Modrzejewski, D., Hartung, F., Wilhelm, R., & Sprink, T. (2020). Genome Edited Crops Touch the Market: A View on the Global Development and Regulatory Environment. In *Frontiers in Plant Science* (Vol 11). Frontiers Media S.A.
- Normile, D. 2019. "Gene-edited foods are safe, Japanese panel concludes." <https://www.sciencemag.org/news/2019/03/gene-edited-foods-are-safe-japanese-panel-concludes>
- Pothering J. (2019, April 10). Europe's Gene Editing Regulation Exposes the Messy Relationship Between Science and Politics. AgFunder Network. <https://agfundernews.com/europes-gene-editing-regulation-exposes-the-messy-relationship-between-science-and-politics>
- Rodríguez-Leal, D., et al. 2017. "Engineering Quantitative Trait Variation for Crop Improvement by Genome Editing." *Cell* 171(2): 470-480.
- Rothan, C., et al. 2019. "Trait discovery and editing in tomato." *Plant J.* 97(1): 73-90.
- Sánchez-León, S., et al. 2017. "Low-gluten, nontransgenic wheat engineered with CRISPR/Cas9." *Plant Biotechnol J.* 16(4): 902-910.
- Schneider, K., R. Goodrich Schneider, and S. Richardson. 2014. *Genetically Modified Food*. FSHN02-2. Gainesville: University of Florida Institute of Food and Agricultural Sciences. <https://edis.ifas.ufl.edu/fs084>
- United States Department of Agriculture. (2018, March 28) *Secretary Perdue Issues USDA Statement on plant breeding innovation*. (Press Release). <https://www.usda.gov/media/press-releases/2018/03/28/secretary-perdue-issues-usda-statement-plant-breeding-innovation>
- United States Department of Agriculture. (2020(a), May 14) *USDA SECURE Rule Paves Way for Agricultural innovation*. (Press Release). <https://www.usda.gov/media/press-releases/2020/05/14/usda-secure-rule-paves-way-agriculture-innovation>
- United States Department of Agriculture. (2020(b), Part 340-Movement of Organisms Modified or produced through Genetic Engineering. (7 CFR part 340) Author.
- United States Department of Agriculture/Animal and Plant Health Inspection Service. (2022, April 26). History highlight: Aphis begins overseeing AG Biotech. United States Department of Agriculture, Animal and Plant Health Inspection Service. https://www.aphis.usda.gov/aphis/newsroom/stakeholder-info/sa_by_date/sa-2022/aphis50-hh-biotech#:~:text=APHIS'%20first%20major%20biotechnology%20regulation,used%20in%20the%20creation%20process

Van Der Meer, P., Angenon, G., Bergmans, H., Buhk, H. J., Callebaut, S., Chamon, M., Eriksson, D., Gheysen, G., Harwood, W., Hundleby, P., Kearns, P., Mcloughlin, T., & Zimny, T. (2023). The Status under EU Law of Organisms Developed through Novel Genomic Techniques. *European Journal of Risk Regulation*, 14(1), 93–112. <https://doi.org/10.1017/err.2020.105>

Vigouroux, A., & Bikard, D. (2020). CRISPR Tools To Control Gene Expression in Bacteria. *Microbiology and Molecular Biology Reviews*, 84(2). <https://doi.org/10.1128/membr.00077-19>

Voigt, B. (2023). EU regulation of gene-edited plants—A reform proposal. *Frontiers in Genome Editing*, 5. <https://doi.org/10.3389/fgeed.2023.1119442>

Waltz, E. 2016. “Gene-edited CRISPR mushroom escapes US regulation.” *Nature News* 532(7599): 293.

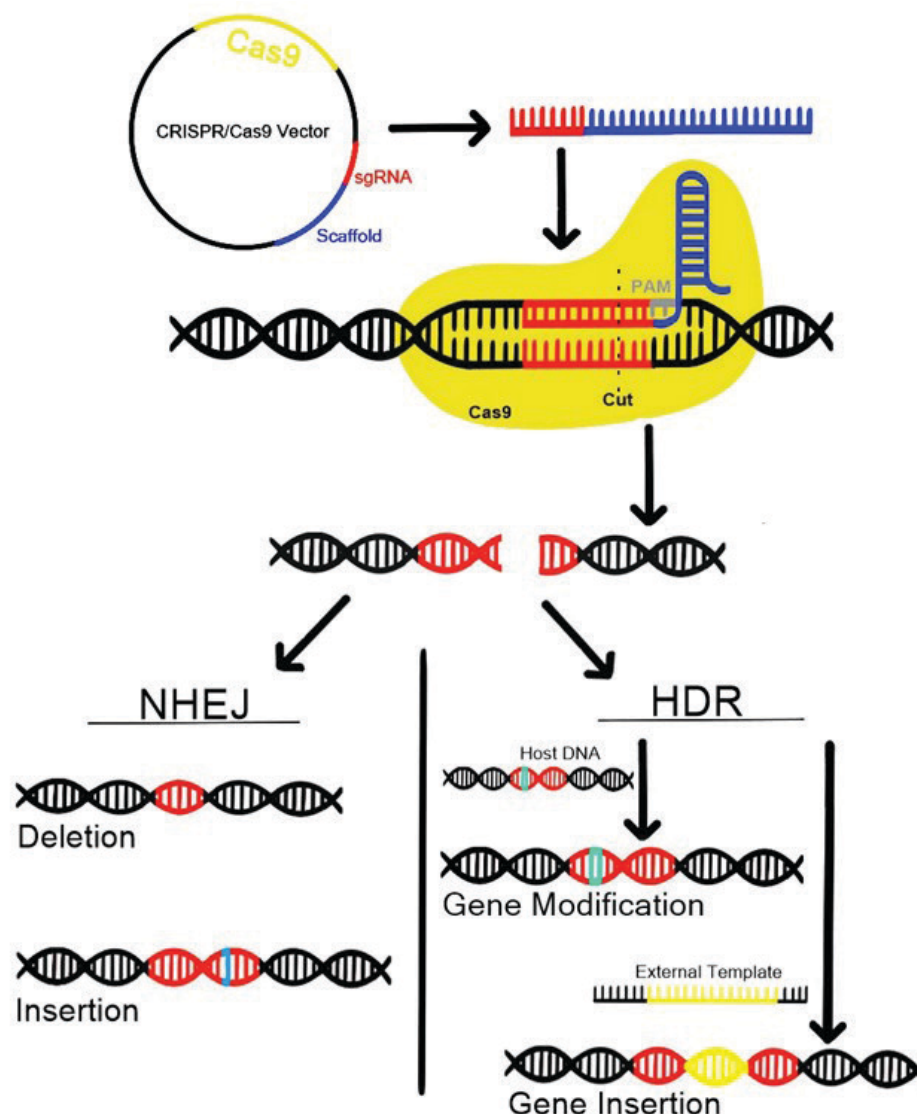


Figure 1. Depiction of CRISPR/Cas9-mediated gene editing.

Table 1. A selection of companies using CRISPR gene editing for crop improvement.

Company	Targeted gene-editing crops
Alora	Rice
Arcadia Biosciences	Wheat
Bayer	Corn, pennycress
Benson Hill Biosystems	Row crops
Cibus	Canola, corn, rice, soybean, wheat
Corteva	Corn
Inari Agriculture	Corn, soybean, wheat
J.R. Simplot	Avocado, potato, strawberry
Nexgen	Tomato
Okanagan Specialty Fruits	Apple
Pairwise	Blackberry, cherry, corn, lettuce, mustard greens, raspberry, soybean
PLANTeDIT	Apple, grape, soybean
Sanatech Seed	Tomato
Syngenta	Corn, rice, soybean, sunflower, tomato, wheat
Tropic Biosciences	Banana and coffee
Yield10 Bioscience	Camelina

Table 2. CRISPR-modified foods still in development and already approved for the market.

Crop	Purpose of gene-editing	Country	Current stage
Alfalfa	Improve quality	United States	Phase III
Apple	Nonbrowning	Canada	Several commercially available varieties—more in development
Avocado	Reduced browning	United States	Research in progress
Cacao	Enhance resistance to <i>Phytophthora tropicalis</i> disease	United States	Research in progress
Camelina	Increase oil content	United States	USDA cleared (2022)—in pre-commercial seed production
Citrus	Citrus greening disease resistance	United States	Research in progress
Corn	Waxy corn, drought resistance, shorter growth height	United States	Field-trial stage
Groundcherry tomato	Improve productivity	United States	Research completed—awaiting approval for market release
Lettuce	Increased nutrient quantity	United States	Commercial release planned (2023)
Potato	Cold storage, reduced acrylamide	United States	Field-trial stage
	Reduced browning	United States	Commercially available
Rice	Improve yield	China	Research continuing on additional varieties
	Salt tolerance	Canada, Vietnam, Kenya	Field-trial stage
Salad greens	Reduced pungency	United States	Commercial release planned (2023)
Soybean	High oleic acid, less saturated fat	United States	Commercially available
Strawberry	Extend shelf life	United States	Research in progress
Tomato	Increase fruit size, yield, and lycopene accumulation	European Union	Field-trial stage
	Virus-resistance	Australia, United States	Field-trial stage
	Increased γ -aminobutyric acid (GABA) content	Japan	Commercially available
<u>Wheat</u>	<u>Reduce gluten content</u>	<u>European Union</u>	<u>Field-trial stage</u>
	High Fiber	United States	USDA cleared (2018)—not commercialized
	Fungal disease resistance	China	Research in progress
White button mushrooms	Nonbrowning	United States	Ready for market—awaiting Food and Drug Administration approval
Information is retrieved from “CRISPR in agriculture: An era of food evolution.” https://www.synthego.com/blog/crispr-agriculture-foods and “United States: Crops/Food” https://crispr-gene-editing-regs-tracker.geneticliteracyproject.org/united-states-crops-food/			