Food Biotechnology & Agricultural Sciences

Received: 2 December 2025 | Revised: 10 December 2025 | Accepted: 17 December 2025
DOI: 10.70734/fbas/215427

REVIEW ARTICLE

CRISPR genome editing technology in the agri-food industry: benefits, challenges and concerns

Edyta Juszczuk-Kubiak[1], Krzysztof Mrozik[2], Natalia Piłka[1], Mateusz Bąk[1], Ewelina Zielińska[2], Monika Kowalczyk[2], Marek Roszko[3]

1. Department of Biotechnology, Prof. Wacław Dąbrowski Institute of Agricultural and Food Biotechnology, State Research Institute, Rakowiecka 36 Str., 02-532 Warsaw, Poland

2. Department Biotechnology, Prof. Wacław Dąbrowski Institute of Agricultural and Food Biotechnology, State Research Institute, Rakowiecka 36 Str., 02-532 Warsaw, Poland

3. Prof. Wacław Dąbrowski Institute of Agricultural and Food Biotechnology, State Research Institute, Rakowiecka 36 Str., 02-532 Warsaw, Poland

Correspondence
edyta.juszczuk-kubiak@ibprs.pl

Department of Biotechnology, Prof. Wacław Dąbrowski Institute of Agricultural and Food Biotechnology, State Research Institute, Rakowiecka 36 Str., Warsaw, Poland

Abstract

The development of genome-editing technologies, mainly clustered regularly interspaced short palindromic repeats/CRISPR-associated protein 9 (CRISPR/Cas9), has transformed modern biotechnology, enabling the precise modification of genetic material across diverse organisms. In the agri-food sector, CRISPR/Cas9 provides an accurate tool for genome editing in crop plants to enhance their yield, stress tolerance, disease resistance, and nutritional content. Unlike the genetic engineering techniques used in genetically modified organisms (GMOs), CRISPR/Cas9 enables precise gene editing without introducing foreign DNA, sparking debates over its classification and regulation within the current GMO framework. While CRISPR/Cas9 technology holds significant promise, its application in the agri-food sector raises ethical, ecological, and socio-economic concerns that necessitate thorough evaluation and transparent governance. Recent European Union (EU) legislative measures seek to establish regulatory pathways that balance innovation with biosafety and public confidence. This brief report examines the benefits, challenges, and public concerns associated with the use of CRISPR/Cas9 technology in the agri-food industry, highlighting its role in advancing a sustainable and responsible food system.

KEYWORDS
New genomic techniques (NGTs), CRISPR/Cas9 technology, the agri-food industry, regulatory and ethical challenges

Introduction

The 21st century presents many new challenges for society, that are threatening our planet. These include the expanding global population and rising food demand, the decline in biological diversity, and the advancing impacts of climate change. By 2050, the human population is projected to reach approximately 9 billion, representing an increase of nearly 2 billion people within a relatively short period of time [Gu et al. 2021]. The growing global population and the expanding food deficit in poor countries pose a significant challenge to the worldwide agri-food sector. This can be addressed by improving crop efficiency and using areas previously deemed unsuitable for cultivation (e.g., soils with high salinity) [Gajardo et al. 2023]. The sustainable use of agricultural land is now more critical than ever, alongside the maintenance of consistent, reliable yields. Achieving this goal requires ongoing advances in the development of cultivated plant varieties to support sustainable food production. The increasing problems caused by plant pests, droughts linked to global warming, and soil degradation are currently serious challenges for the agri-food industry [Massel et al. 2021]. Rapid progress in crop breeding and food production, therefore, requires alternative solutions that utilize the latest advances in genome editing [Singh et al. 2022]. New genomic techniques (NGT) are promising tools for transforming modern biotechnology, enabling precise, efficient, and sustainable improvements in plant and animal breeding [Villiger et al. 2024]. These techniques include cisgenesis (CRISPR/Cas9), targeting mutagenesis with site-specific nucleases (TALEN, ZNF),

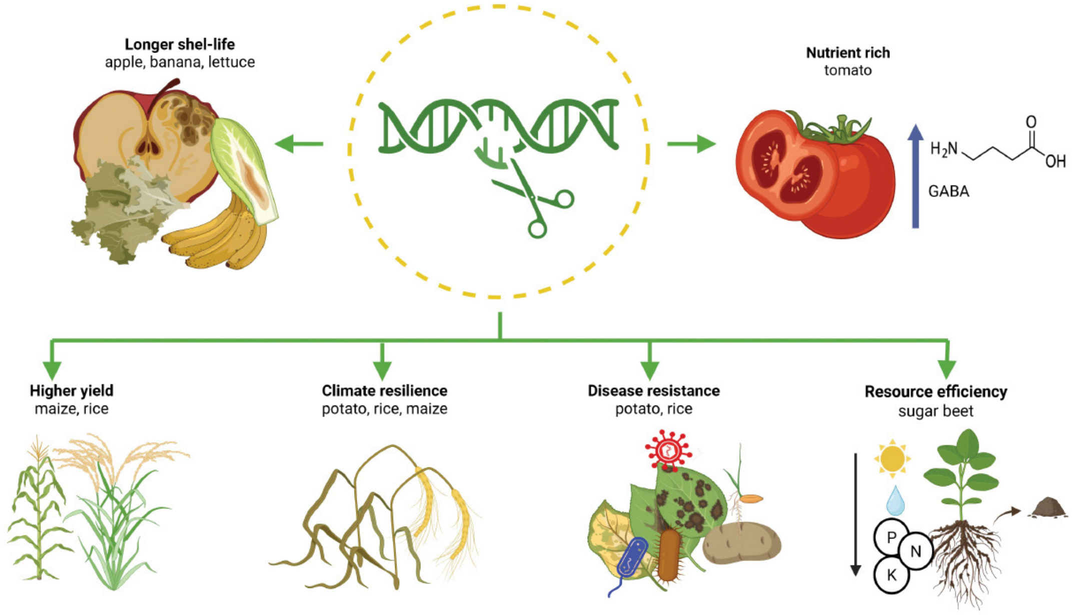

Figure 1. Schematic representation of CRISPR/Cas9 application in the agri-food sector. Figure created with BioRender.com (https://BioRender.com).

oligonucleotide-directed mutagenesis (ODM), RNA-dependent DNA methylation (RdDM), and grafting onto genetically modified (GM) rootstocks [Ordonio et al. 2023]. The agri-food sector anticipates these methods because the genome editing of plants offers promising alternatives to genetically modified organisms (GMOs) [Podevin et al. 2012].

Since the discovery of the CRISPR/Cas9 mechanism in 2012, remarkable advances have been achieved in medicine, biotechnology, agriculture, and animal sciences [Jinek et al. 2012]. To date, thousands of genome-editing experiments have been conducted worldwide in both prokaryotic and eukaryotic systems, demonstrating the broad applicability and efficiency of this technology [Li et al. 2023]. Currently, research institutions and biotechnology laboratories worldwide are actively using genome-editing technologies to improve a wide range of crop species [Zaman et al. 2021]. The use of these tools offers enormous potential to develop improved plant varieties with higher yields and better-quality traits in a relatively short 2–3 years, compared to traditional breeding methods [Long et al. 2018]. Because CRISPR/Cas9 technology has already been extensively reviewed in the scientific literature [Gao et al. 2021], this report provides a concise overview of genome-editing applications, particularly CRISPR/Cas9, in the agri-food sector. Specifically, the benefits, potential challenges, legislative restrictions, and social issues associated with implementing CRISPR/Cas9 technology in the food supply chain are summarized.

CRISPR Technology – potential application in the agri-food sector

Unlike traditional genetically modified organisms (GMOs), which usually depend on inserting foreign DNA, CRISPR/Cas9 makes highly precise modifications within the plant's own genome [Lanigan et al. 2020; Villiger et al. 2024; Gilbertson et al. 2025]. These edits often resemble naturally occurring genetic variations that promote biodiversity and adaptation to environmental challenges [Gilbertson et al. 2025]. As a result, CRISPR-based genome editing is increasingly being seen as a safe, targeted, and versatile alternative to both conventional breeding and transgenic modifications, offering a tool for quickly developing improved cultivars [Asmamaw, Zawdie 2021; Acevedo-Garcia et al. 2017]. CRISPR/Cas9 has been used across major crop species, including rice, wheat, maize, and barley, to improve key agronomic traits such as yield, quality, stress resilience, disease resistance, herbicide tolerance, and nutritional value [Lanigan et al. 2020; Villiger et al. 2024] [Fig.1].

For example, Miao et al. [2018] used the CRISPR/Cas9 system to create a rice line in which the Pyl1, Pyl4, and Pyl6 genes were simultaneously knocked out. The resulting triple mutant showed improved agronomic performance, including increased grain yield, longer panicles, more primary and secondary branches, and fewer tillers compared to wild-type plants. In another study, coordinated CRISPR/Cas9-mediated disruption of three grain-weight–related genes, Gw2, Gw5, and Tgw6, led to a significant increase in grain size and overall grain mass [Xu et al. 2016]. Additionally, knocking out OsAAP3, which encodes an amino acid transporter involved in regulating nutrient distribution within the plant, was found to enhance tiller number and grain yield without impairing grain quality [Lu et al. 2018].

CRISPR/Cas9 has been used to modify plant genes conferring resistance to biotic stresses, including bacterial, fungal, and viral infections [Ma et al. 2019; Jung et al. 2018; Mishra et al. 2021; Shou 2021]. For example, researchers developed a powdery mildew–resistant wheat line by using CRISPR/Cas9 to introduce a targeted modification in the mlo1 gene, which plays a key role in mediating susceptibility to this fungal disease [Wang et al. 2014]. The CRISPR/Cas9 genome-editing system has been used to simultaneously edit the promoter regions of Sweet11, Sweet13, and Sweet14 to produce rice lines exhibiting broad-spectrum resistance to Xanthomonas oryzae pv. Oryzae (Xoo) [Oliva et al. 2019]. In turn, Malnoy et al. [2016] used CRISPR/Cas9 to edit Dipm-1, Dipm-2, and Dipm-4 in apple protoplasts, resulting in increased fire blight resistance. Conversely, CRISPR/Cas9 has been used to extend the shelf life of tomatoes by disrupting the RIN (Ripening Inhibitor) gene, which encodes a MADS-box transcription factor crucial for fruit ripening regulation [Jung et al. 2018]. This genome-editing strategy has been successfully applied across several tomato cultivars, including Ailsa Craig, Mamirio, and Golden Bell [Ito et al. 2015; Jung et al. 2018]. In the United States, DuPont Pioneer applied CRISPR/Cas9 genome editing to maize to modify its starch composition. This approach produced a maize line that synthesizes starch almost entirely as amylopectin. The targeted locus was the Waxy (Wx1) gene, which encodes a granule-bound starch synthase responsible for amylose biosynthesis [Wu et al. 2020]. The disruption of wx1 reduces amylose production, shifting starch composition towards nearly 100% amylopectin and resulting in the characteristic "waxy maize" phenotype [Globus, Qimron 2018]. CRISPR/Cas9 has also been employed to knock out the Orange (Or) gene to enhance carotenoid accumulation, particularly β-carotene in rice [Zhu et al. 2019]. The technology has further been used to disrupt the Gw2 gene, producing mutant lines with increased protein content and higher levels of essential dietary elements, including Fe, Zn, K, P, and Ca, in the rice endosperm [Achary, Reddy 2021].

Conversely, CRISPR/Cas9 techniques can also be used to enhance the nutritional and health-related traits of crop plants [Jouanin et al. 2020; Mackon et al. 2023]. Sánchez-León et al. [2018] developed a low-gluten wheat line with approximately an 85% reduction in immunoreactivity by targeting conserved regions of the α-gliadin gene family. More recently, Liu et al. [2023] demonstrated that the precise editing of two γ-gliadin genes, Gli-γ1-1D and Gli-γ2-1B, improved wheat end-product quality and decreased the presence of gluten epitopes linked to celiac disease. Another example includes a GABA-enhanced tomato produced through multiplex CRISPR/Cas9 editing, which targeted five genes involved in GABA metabolism: three pyruvate-dependent GABA transaminases (GABA-TP 1, GABA-TP 2, and GABA-TP 3), the cationic amino acid transporter CAT9, and SSADH (succinate semialdehyde dehydrogenase) [Li et al. 2018]. As a result, GABA-enriched tomato has been commercially available in Japan since 2021 [Ahmad 2022]. In another study, Jing et al. [2021] employed the CRISPR/Cas9 system to knock out Gmfatb1, a gene encoding a fatty acyl carrier protein thioesterase, which significantly reduced the levels of two saturated fatty acids in soybean mutants. Another instance involves the CRISPR/Cas9-edited non-browning mushroom, in which the Ppo1 gene was knocked out to prevent enzymatic browning [Waltz 2016]. Similarly, Maioli et al. [2020] used CRISPR/Cas9 to knock out three Ppo genes (Smelppo 4, Smelppo 5, and Smelppo 6) in potato, resulting in a non-browning phenotype. Furthermore, CRISPR/Cas9 has been used to modify a variety of genes associated with key agronomic and quality traits in rice. For example, editing Fad2-1/Fad2 increased oleic and linoleic acid content [Bahariah et al. 2021], while the modification of Gs9 improved grain shape [Zhao et al. 2018]. Additionally, CRISPR/Cas 9 has been used to enhance rice eating and cooking quality by introducing aroma-related traits into non-aromatic cultivars. For instance, the non-aromatic rice variety ASD16 was converted into an aromatic type by generating novel Osbadh2 alleles using CRISPR/Cas9 [Ashokkumar et al. 2020]. The Osbadh 2 gene is a critical factor in rice fragrance, and its targeted modification allows breeders to develop new aromatic lines without affecting other desirable agronomic qualities.

Research on plant genome editing is also progressing in Poland. Several research groups are actively involved in this field, supported by both national and international collaborations. Key institutions include the Institute of Biochemistry and Biophysics of the Polish Academy of Sciences (PAN) in Warsaw and the Institute of Bioorganic Chemistry in Poznań. A notable earlier achievement by Polish researchers was the development of a method to engineer lettuce cells to produce a hepatitis B vaccine through transformation with Agrobacterium tumefaciens LBA4404 [Kapusta et al. 1999]. Researchers at the University of Wrocław improved flax traits through non-GMO, epigenetically based methods. Specifically, they used RNA-dependent DNA methylation (RdDM) to regulate the levels of key metabolites, including isoprenoids, phenylpropanoids, and glutathione [Szopa, Kulma 2022]. These epigenetic changes aim to boost pathogen resistance, increase seed and fiber yields, and enhance the quality of flax oil and fiber. The research has advanced to the stage where seeds have been produced from the first fungus-resistant flax lines, with plant material cultivated on a one-ton scale [Szopa, Kulma 2022]. More recently, CRISPR/Cas9 genome editing was employed by researchers from the Institute of Plant Genetics, PAS, to disrupt three candidate resistance genes identified by genome-wide association mapping in the clubroot-resistant Arabidopsis accessions Est-1 and Uod-1. CRISPR/Cas9-mediated knockout of Rpb1 abolished resistance to Plasmodiophora brassicae, showing that Rpb1 is required to activate downstream defense pathways [Ochoa et al. 2023]. CRISPR/Cas9 technologies have also been used to manipulate crop genomes by scientists at the Institute of Plant Breeding and Acclimatization – State Research Institute (IHAR-PIB) in Radzików [Gasparis et al. 2019]. Researchers used the CRISPR-Cas9 gene-editing system to inactivate two specific genes, HvCKX1 and HvCKX3, in barley, which are involved in cytokinin metabolism, a group of plant hormones that regulate cell growth and division. The results showed that knocking out HvCKX1 and HvCKX3 affected cytokinin metabolism and significantly altered root development, particularly in HvCKX1 mutants. In summary, the work carried out by the Department of Genetic Engineering with the Department of Functional Genomics has resulted in two patents (https://ihar.edu.pl).

Genome editing tools are also increasingly used in modern livestock breeding, driven by the need to breed animals with precisely defined, desirable traits. Sequencing livestock genomes has enabled researchers to identify thousands of metabolic pathways and genes responsible for specific production traits [Liu et al. 2024]. The most desirable traits in animals include rapid growth, significant muscle gain, high milk yield, and the presence of bioactive components in meat. Current research provides genome editing to produce milk with properties similar to human milk, thereby eliminating food allergies [Popova et al. 2023; Hadri et al. 2025]. Ni et al. [2014] successfully edited the β-lactoglobulin (Blg) gene using the CRISPR/Cas9 system in goats. Similarly, Knockout of the α-lactalbumin (Lalba) and β-lactoglobulin (Blg) genes in goats resulted in milk with reduced immunogenic protein content, rendering it suitable for individuals with allergies [Zhou et al. 2017].

Examples of CRISPR/Cas9-mediated genome modifications in crops used within the agri-food sector are shown in Table 1.

Crop name	Gene symbol	Gene function	Editing methods	Trait improvement	References
rice	*Pyl1, Pyl4, Pyl6*	regulate plant growth	knockout	Promote rice growth and productivity	Miao et al. [2018]
rice	*OsSNB*	regulate flower organ development and grain shape	knockout	Increase the grain length, grain width and 1000-grain weight	Ma et al. [2019]
rice	*HvCKX1*	catalyze the irreversible degradation of active cytokinins	knockout	Increase in grain yield and root biomass	Gasparis et al. [2019]
Wheat	*TaGASR7*	grain length and weight	knockout	1000-grain weight	Zhang et al. [2016]
Wheat	*TaGW2*	encoding RING E3 ligase	knockout	Increase the length and width of grains	Zhang et al. [2018]
Rice	*OsBADH2*	encoding betaine aldehyde dehydrogenase	knockout	Increase the flavour	Shan et al. [2015]
rice	*Rc*	production of red pigment	knockout	Increase in the production of proanthocyanidins and anthocyanidins	Zhu et al [2019]
Spring barley	*Waxy*	catalyse the synthesis of amylose	knockout	Reduce amylose content	Fan [2021]
maize	*Wx1*	encoding starch synthase	knockout	Increase maize amylopectin content	Zhu et al. [2020]
tomato	*Ant1*	regulate plant growth	In-situ-specific activation	Increase anthocyanin content	Ito et al. [2015]
rice	*OsALS OsU3*	encoding the acetolactate synthase 1	knockout	Herbicides resistance	Sun et al. [2016]
soybean	*GmFATB1*	encoding the FATB protein	knockout	Reduce the contents of two saturated fatty acids	Shou [2021]
rice	*OsSEC3A*	interacted with rice SNAP25-type SNARE protein OsSNAP32 and phosphatidylinositol-3-phosphate	knockout	enhanced resistance to the fungal pathogen *Magnaporthe oryzae*	Ma et al. [2018]
potatoes	*StDND1, StCHL1, StDMR6-1*	disease susceptibility genes	knockout	increase resistance against late blight	Kieu et al. [2021]
chili pepper	*CaERF28*	disease susceptibility gene	knockout	increased anthracnose fungus (*C. truncatum*) resistance	Mishra et al. [2021]
rice	*Cry2AX1*	synthetic gene	knockout	resistance to leaf folders (*C. medinalis*) and rice yellow and stem borer (*S. incerulas*)	Rajadurai et al. [2018]
wheat	*Pdil5-1, eIF4E*	encoding protein disulfide isomerase (PDI), a type of endoplasmic reticulum (ER)-resident chaperone protein.	knockout	resistance against the yellow mosaic virus	Kan et al. [2023]

Table 1. Examples of genes from various crops that have been modified by the CRISPR/Cas9 system.

CRISPR Technology – concerns and challenges for the agri-food sector

The agri-food sector faces many challenges [Devaux et al. 2021]. There is a strong demand for crops developed with modern technologies that avoid controversy or social issues. Developing innovative genome editing tools based on cisgenesis meets these needs [Shew et al. 2018]. The simplicity and stability of these methods offer excellent opportunities for the agricultural and food industries. They enable faster, more efficient development of new, high-yielding varieties that are resistant to diseases and environmental stresses, producing highly nutritious food. This will help address issues related to sustainable development and the future of agriculture.

A significant challenge for the agri-food sector will be maintaining high safety standards for genome-edited food and agricultural environments [Domingo 2025]. Food placed on the consumer market must be safe, and genetically modified crops released into the environment should not harm biodiversity or protected areas [Tsatsakis et al. 2017]. The rapid development of innovative genome-editing technologies has raised many questions about ethics, biosafety, agriculture, and intellectual property rights [Davison, Ammann 2017]. As with previous debates on genetic engineering tools, concerns have emerged about the potential misuse of applied technologies. Given the development of new genomic engineering techniques, one of the main challenges for the agri-food market is to actively engage in establishing clear approval procedures for genome-edited agricultural products and food within the EU [Davison, Ammann 2017; Brookes, Smyth 2024]. It is essential to differentiate among various genome-editing applications for regulatory assessment within existing legal frameworks. Some applications may lead to genetically modified plants, whereas others may produce plants similar to those made through traditional breeding methods. The latter do not cross species barriers, resulting in plants that could occur naturally or through conventional breeding. The key factor for regulatory classification should be the nature of the trait or modification in the new crop variety, not the technology used [Brookes, Smyth 2024]. Of course, the path to commercializing research findings and integrating genome-edited products into the agri-food sector remains lengthy. Nonetheless, research results have already sparked interest from the private sector. Biotechnology companies that commercialize CRISPR/Cas9 technology expect the agri-food sector to become one of the most lucrative areas to produce genome-edited food [Kalaitzandonakes et al. 2023]. It is also important to remember that developing modern strategies for producing genome-edited products will require increased financial investment in innovative research and commercialization, from both private and public sectors. This is vital to ensure that precise, genome-based breeding techniques do not become the exclusive domain of a few large international corporations, which use them only in major crop species that guarantee quick returns and high profits [Bohle et al. 2024]. One potential solution is to enhance public funding for agricultural research.

Regulatory Framework for CRISPR Technology in the Agri-Food Sector

Although new genomic techniques are promising, they still encounter legal hurdles within the EU. The main regulatory question is whether CRISPR-edited organisms should be treated like genetically modified organisms (GMOs) or like conventionally bred plants, especially when no foreign DNA is added. Currently, regulations only cover genetically modified organisms (GMOs) (Directive 2001/18/EC and Regulation (EC) No. 1829/2003) [Bohle et al. 2024]. These do not apply to NGTs. In July 2018, the Grand Chamber of the European Court of Justice (ECJ) determined that the environmental and health risks associated with plants created by NGTs are comparable to those posed by producing and distributing GMOs through transgenesis. As a result, the ECJ concluded that Directive 2001/18/EC fully applies to NGTs [European Court of Justice, Confédération Paysanne 2018]. In 2023, the European Commission proposed a draft regulation to support the market entry of new genomic techniques (NGTs). Plants were categorized into two groups: those with a single genomic modification (NGT1) and those with multiple modifications (NGT2) [EFSA 2025]. However, Poland did not endorse the proposal and stated that it would continue to develop its own regulations to address NGTs' specific features. Nonetheless, several initiatives have been established within the EU to help overcome these regulatory challenges. Among them are the COST Action PlantEd (2019–2023) [https://plantgenomeediting.eu/] and the EU-SAGE network (Sustainable Agriculture through Genome Editing) [https://www.eu-sage.eu/], both of which aim to promote informed discussion and disseminate science-based knowledge on new breeding technologies.

In the US, the agencies responsible for GMO regulation are the US Food and Drug Administration (FDA), U.S. Environmental Protection Agency (EPA), and US Department of Agriculture (USDA), which ensure GMO safety for human consumption, animal feed, the environment, and industry. The coordination of these agencies to regulate and monitor GMOs is managed by the Coordinated Framework for Regulation of Biotechnology, implemented in 1986 [Coordinated Framework 2025]. According to this framework, new whole foods do not need to be proven safe before being released onto the market, resulting in a wide variety of GMO crops being cultivated in the US.

Canada developed a system that places a greater emphasis on risk assessment, approving plants with novel traits for human consumption on a case-by-case basis [Smyth 2014]. It is worth noting that Canadian law does not differentiate between novel traits obtained through genome engineering and those developed via traditional breeding. The legislation introduced in 1994 has led to the widespread adoption of genetically modified (GM) canola, corn, and soybeans [Smyth 2014]. Interestingly, unlike in the United States, Canadian law does not permit patenting multicellular organisms [Maher 1997].

The United Kingdom recently updated its legislation through two key acts [Freeland et al. 2024]. In 2022, the Environmental Protection Act was enacted, allowing scientists to carry out GMO field trials more easily. In 2023, the Genetic Technology (Precision Breeding) Act was passed, introducing the term "precision-bred organisms" for organisms created with NGTs and exempting them from the regulatory requirements of GMOs, moving away from previous EU-style regulations [Watson and Hayta, 2024]. The new regulation will enable the broader use of organisms developed with NGTs [Tachikawa, Matsuo 2024]. Additionally, China has a comprehensive regulatory framework for approving GMO crops, comprising four documents: "Administrative Measures on the Safety Assessment of Agricultural GMOs," "Measures for the Examination and Approval of Main Crop Varieties," "Measures for the Administration of Production and Operation Licensing of Crop Seeds," and "Nomenclature of Agricultural Plant Varieties" [Liang et al. 2022]. Under these regulations, GM cotton and papaya are widely cultivated in China, with several varieties of corn, soybean, and rice already approved for cultivation but not yet for commercial production [Sun et al. 2024].

Japan's legislative system introduced site-directed nuclease (SDN) technologies, categorizing genome-editing technologies into SDN-1, -2, and -3. SDN-1 involves genome modifications that result in indels and deletions, and organisms produced through this method are regulated similarly to non-GMO organisms. SDN-2 refers to organisms with base substitutions, while SDN-3 involves organisms with foreign genes introduced. Both SDN-2 and SDN-3 require a template and are regulated as GMO organisms, requiring safety assessments and mandatory labelling [Kondo, Taguchi 2022]. Currently, several genetically modified products are available on the market, including GABA-enriched tomatoes, sea bream, high-growth tiger puffer fish, waxy maize, and olive flounder. All except for waxy maize were developed by start-ups in Japan [Tachikawa, Matsuo 2024]. Like Japan, Australia also developed a similar legislative system, under which organisms created with SDN-1 are not regulated as GMOs [Thygesen 2024].

In Latin America, GMO regulations vary between different countries. Argentina is recognized as a leader in GMO production, with 48 approved varieties for commercial cultivation and being one of the largest producers of GM crops [Dederer, Hamburger 2019]. The organization responsible for GMO regulation in Argentina is CONABIA (Comisión Nacional Asesora de Biotecnología Agropecuaria). Brazil is another major producer of GM crops, with more than 100 modified varieties approved for cultivation [Genome Editing in Latin America 2025]. Brazil has specific regulations regarding GMOs and has ratified the Cartagena Protocol on Biosafety (CPB), which oversees the transfer of GMO organisms between countries. Peru and Bolivia have adopted stricter regulations. Bolivia had a moratorium on all GMOs until 2005 and has struggled to establish a clear framework for the cultivation, importation, and development of genetically engineered organisms. Peru is also slow to update its laws regarding GMOs, as it implemented the moratorium on GMO organisms in 2011 [Zarate et al. 2023]. Mexico, which previously permitted the cultivation and human consumption of GMOs, issued a presidential decree in 2023 that replaced the 2020 regulatory framework and banned the cultivation and import of GM corn [Roca et al. 2023].

Ethical and social perspectives on CRISPR technology in the agri-food sector

New genomic techniques offer high control and accuracy in gene editing, with significant implications for agriculture and food security [Watson, Hayta 2024]. However, organisms and products produced using these methods often face the same scrutiny as traditional GMOs, and public awareness of genetic engineering techniques remains limited. The main challenge for the agri-food sector remains public acceptance, which remains unresolved [Rzymski, Królczyk 2016]. Primarily, active debate and education are needed to persuade society that breeding progress enabled by innovative genomic methods can meet the growing demand for food. Unfortunately, innovations in food production enabled by genomic technologies currently spark controversy, misconceptions, and unfounded fears. The average citizen has little knowledge of biotechnology, genetic engineering, or the potential of genome editing in crop breeding and production. This knowledge is often fragmented and taken out of context. It usually consists of biased opinions rather than accurate, thought-provoking information that encourages independent reasoning. This lack of knowledge and reliable information likely fuels many disputes regarding these innovative technologies. Regardless of scientists' opinions, government policies, or environmental protests, the ultimate decision to accept or reject products developed through genome editing rests with consumers [Bohle et al. 2024]. In the USA, Canada, Belgium, France, and Australia, 56%, 47%, 46%, 30%, and 51% of respondents, respectively, reported they would consume both GM and CRISPR-modified food [Shew et al. 2018]. The same study found that respondents were more inclined to eat CRISPR-modified food than GMO food, suggesting an opportunity to reduce skepticism towards NGT-modified organisms. In Europe, consumer awareness of NTG use in the agri-food sector remains limited. According to a 2019 Eurobarometer survey, only 21% of Europeans had heard of genome editing [EFSA 2019]. In Poland, the figure was 16%, compared to 62% in Finland, the best-informed country [EFSA 2019]. The promising development of the CRISPR/Cas9 tool poses specific societal challenges and raises concerns about potential misuse, which could have disastrous consequences. However, one certainty is that nature will never cease to inspire us with its biological toolkit. As scientists, we are motivated to explore the limits of the natural world and uncover its fundamental mechanisms, some of which, such as CRISPR/Cas9, could serve as tools for future discoveries. The tools themselves do not pose a threat, and it is hoped that CRISPR/Cas9 technology will fulfil its promises, provided it is used responsibly and carefully. Many companies also utilize this technology to produce high-quality food and feed crops. Products made with CRISPR/Cas9 editing contain no foreign DNA, and the process can be carried out in compliance with all legal standards and regulations set by agencies that often oppose genetic modification.

Conclusions

CRISPR/Cas9 has become one of the most transformative tools in modern molecular biology, offering a precise, efficient, and adaptable platform for targeted genome editing. In the agri-food industry, its application has already shown significant potential to introduce beneficial traits, such as improved nutritional profiles, greater resilience to biotic and abiotic stresses, and longer post-harvest shelf life. Unlike traditional genetic modification, CRISPR-based editing can produce changes that closely resemble naturally occurring mutations, removing the need for foreign DNA. This difference not only boosts the likelihood of public acceptance but also simplifies regulatory assessment in jurisdictions with science-based frameworks. Furthermore, CRISPR/Cas9 has become essential in functional genomics, helping to uncover gene–trait relationships and facilitating the swift development of next-generation crop varieties. Its uses also extend beyond plants to microorganisms employed in fermentation, probiotic formulations, and nutritional enhancement, thereby opening up new avenues to improve food quality and safety.

Despite these advances, the EU regulatory environment presents a significant obstacle to the adoption of genome-edited crops. Although many technical challenges of the CRISPR/Cas systems have already been addressed or are likely to be overcome through ongoing research, the EU currently regulates genome-edited plants under the same legal framework as GMOs, regardless of the type or degree of genetic modification. This regulatory approach greatly limits the cultivation and commercialization of genome-edited varieties, making the commercial viability of such crops largely feasible for major commodity species such as maize and soybean, where the high costs of regulatory compliance can be absorbed, typically by large multinational firms. Consequently, the broader application of precise genome-editing technologies in European plant breeding remains limited, despite their scientific potential and potential contributions to sustainable agri-food development.

Source of Funding

This work was supported by the Minister of Agriculture and Rural Development, Agreement NO. DRE.prz.070.1.2025, tasks 12/32.

References

1. Acevedo-Garcia, J., Spencer, D., Thieron, H., Reinstädler, A., Hammond-Kosack, K., Phillips, A.L., Panstruga, R. mlo-based powdery mildew resistance in hexaploid bread wheat generated by a non-transgenic TILLING approach. Plant Biotechnol J. 2017, 15(3), 367-378.
2. Achary, V.M.M., Reddy, M.K. CRISPR-Cas9 mediated mutation in GRAIN WIDTH and WEIGHT2 (GW2) locus improves aleurone layer and grain nutritional quality in rice. Sci. Rep. 2021, 11(1), 1–13.
3. Ahmad, S., Tang, L., Shahzad, R., Mawia, A.M., Rao, G.S., Jamil, S., Wei, C., Sheng, Z., Shao, G., Wei, X., Hu, P., Mahfouz, M.M., Hu, S., Tang, S. CRISPR-Based Crop Improvements: A Way Forward to Achieve Zero Hunger. J. Agric. Food Chem. 2021, 69(30), 8307-8323.
4. Ahmad, A., Munawar, N., Khan, Z., Qusmani, A.T., Khan, S.H., Jamil, A., Ashraf, S., Ghouri, M.Z., Aslam, S., Mubarik, M.S., Munir, A., Sultan, Q., Abd-Elsalam, K.A., Qari, S.H. An outlook on global regulatory landscape for genome-edited crops. Int. J. Mol. Sci. 2021, 22(21), 11753.
5. Ahmad, A., Munawar, N., Khan, Z., Qusmani, A.T., Khan, S.H., Jamil, A., Ashraf, S., Ghouri, M.Z., Aslam, S., Mubarik, M.S., Munir, A., Sultan, Q., Abd-Elsalam, K.A., Qari, S.H. An outlook on global regulatory landscape for genome-edited crops. Int. J. Mol. Sci. 2021, 22(21), 11753.
6. Angon, P.B., Mondal, S., Akter, S., Sakil, M.A., Jalil, M.A. Roles of CRISPR to mitigate drought and salinity stresses on plants. Plant Stress 2023, 8, 100169.
7. Anzalone, A.V., Randolph, P.B., Davis, J.R., Sousa, A.A., Koblan, L.W., Levy, J.M., Chen, P.J., Wilson, C., Newby, G.A., Raguram, A., Liu, D.R. Search-and-replace genome editing without double-strand breaks or donor DNA. Nature. 2019, 576(7785), 149-157.
8. Ashokkumar, S., Jaganathan, D., Ramanathan, V., Rahman, H., Palaniswamy, R., Kambale, R., Muthurajan, R. Creation of novel alleles of fragrance gene OsBADH2 in rice through CRISPR/Cas9-mediated gene editing. PLoS One 2020, 15(8), e0237018.
9. Asmamaw, M., Zawdie, B. Mechanism and Applications of CRISPR/Cas-9-Mediated Genome Editing. Biol. Targets Ther. 2021, 15, 353–361.

10. Bahariah, B., Masani, M.Y.A., Rasid, O.A., Parveez, G.K.A. Multiplex CRISPR/ Cas9-mediated genome editing of the FAD2 gene in rice: a model genome editing system for oil palm. J. Genet. Eng. Biotechnol. 2021, 19(1), 86.
11. Bohle, F., Schneider, R., Mundorf, J., Zühl, L., Simon, S., Engelhard, M. Where does the EU-path on new genomic techniques lead us? Front Genome Ed. 2024, 6, 1377117.
12. Brookes, G., Smyth, S.J. Risk-appropriate regulations for gene-editing technologies. GM Crops & Food, 2024, 15(1), 1–14.
13. Caplan, A.L., Parent, B., Shen, M., Plunkett, C. No time to waste - the ethical challenges created by CRISPR. EMBO Rep. 2015, 16, 1421–1426.
14. Capps, B., Chadwick, R., Joly, Y., Mulvihill, J.J., Lysaght, T., Zwart, H. Falling giants and the rise of gene editing: ethics, private interests and the public good. Hum. Genomics. 2017, 11(1), 20.
15. Chakraborty, A., Wylie, S.J. Gene editing for allergen amelioration in plants – a review. Plant Gene. 2024, 40, 100476.
16. Davison, J., Ammann, K. New GMO regulations for old: Determining a new future for EU crop biotechnology. GM Crops Food. 2017, 8(1), 13-34.
17. Dederer, H.-G., Hamburger, D., Eds. Regulation of Genome Editing in Plant Biotechnology: A Comparative Analysis of Regulatory Frameworks of Selected Countries and the EU. Springer International Publishing, Cham, 2019.
18. Devaux, A., Goffart, J.P., Kromann, P., Andrade-Piedra, J., Polar, V., Hareau, G. The Potato of the Future: Opportunities and Challenges in Sustainable Agri-food Systems. Potato Res. 2021, 64(4), 681-720.
19. Domingo, J.L. Genetically modified crops: balancing safety, sustainability, and global security. Environ. Res. 2025, 286(Part 2), 122892.
20. EFSA (European Food Safety Authority). New genomic techniques. EFSA, 29 August 2025. Available online: https://www.efsa.europa.eu/en/topics/new-genomic-techniques.
21. European Court of Justice. Confédération Paysanne, Judgement of the Court (Grand Chamber), 2018, Case C-528/16. Available online: http://curia.europa.eu/juris/document/document.jsf?docid=204387&doclang=EN.
22. European Food Safety Authority. Eurobarometer 2019: Food Safety in the EU. EFSA, 2019. Available online: https://www.efsa.europa.eu/sites/default/files/corporate_publications/files/Eurobarometer2019_Food-safety-in-the-EU_Full-report.pdf. Accessed 27 October 2025.
23. Fan, S. Produce New Glutinous Barley Using CRISPR/Cas9 System. Qinghai Normal University; Qinghai, China: 2021.
24. Freeland, L.V., Phillips, D.W., Jones, H.D. Precision Breeding and Consumer Safety: A Review of Regulations for UK Markets. Agriculture. 2024, 14, 1306.
25. Gajardo, H.A., Gómez-Espinoza, O., Boscariol Ferreira, P., Carrer, H., Bravo, L.A. The Potential of CRISPR/Cas Technology to Enhance Crop Performance on Adverse Soil Conditions. Plants. 2023, 12(9):1892.
26. Gao, C. Genome engineering for crop improvement and future agriculture. Cell. 2021, 184(6), 1621-1635.
27. Gasparis, S., Przyborowski, M., Kała, M., Nadolska-Orczyk, A. Knockout of the HvCKX1 or HvCKX3 gene in Barley (Hordeum vulgare L.) by RNA-guided Cas9 nuclease affects the regulation of cytokinin metabolism and root morphology. Cells. 2019, 8(8), 782. doi.org/10.3390/cells8080782
28. Gilbertson, L., Puchta, H., Slotkin, R.K. The future of genome editing in plants. Nat. Plants. 2025, 11, 680–685.
29. Globus, R., Qimron, U.A technological and regulatory outlook on CRISPR crop editing. J. Cell. Biochem. 2018, 119, 1291–1298.
30. González Castro, N., Bjelic, J., Malhotra, G., Huang, C., Alsaffar, S.H. Comparison of the feasibility, efficiency, and safety of genome editing technologies. Int. J. Mol. Sci. 2021, 22, 10355.
31. Gostimskaya, I. CRISPR-Cas9: A history of its discovery and ethical considerations of its use in genome editing. Biochem. Biokhimiia. 2022, 87, 777–788.
32. Gu, D., Andreev, K., Dupre, M.E. Major trends in population growth around the world. China CDC Wkly. 2021, 3(28), 604-613.
33. Hadri, S.H., Tariq, A., Asif, S., Abid, S., Jabeen, M., Azam, A., Tanzeem, S. CRISPR-Cas9 knockout of the β-lactoglobulin gene in dairy animals: a review. Food Humanity. 2025, 4, 100642.
34. Hemalatha, P., Abda, E.M., Shah, S., Venkatesa Prabhu, S., Jayakumar, M., Karmegam, N., Kim, W., Govarthanan, M. Multi-faceted CRISPR-Cas9 strategy to reduce plant based food loss and waste for sustainable bio-economy – A review. J. Environ. Manage. 2023, 332, 117382.
35. Hu, H., Yu, F.A CRISPR/Cas9-Based System with Controllable Auto-Excision Feature Serving Cisgenic Plant Breeding and Beyond. Int. J. Mol. Sci. 2022, 23(10), 5597.
36. Hussain, B., Lucas, S.J., Budak, H. CRISPR/Cas9 in plants: at play in the genome and at work for crop improvement. Brief Funct. Genomics. 2018, 17(5), 319-328.
37. Inter-American Development Bank. Genome Editing in Latin America: Regional Regulatory Overview. Accessed: 23 October 2025. Available online: https://publications.iadb.org/en/genome-editing-latin-america-regional-regulatory-overview.
38. ISAAA. Gene-edited high oleic soybean oil now available in the US. Accessed: 26 November 2024. Available online: https://www.isaaa.org/kc/cropbiotechupdate/article/default.asp?ID=17345
39. Ito, Y., Nishizawa-Yokoi, A., Endo, M., Mikami, M., Toki, S. CRISPR/Cas9-mediated mutagenesis of the RIN locus that regulates tomato fruit ripening. Biochem. Biophys. Res. Commun. 2015, 467:76–82. doi: 10.1016/j.bbrc.2015.09.117.
40. Jinek, M., Chylinski, K., Fonfara, I., Hauer, M., Doudna, J.A., Charpentier, E.A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity. Science. 2012, 337(6096), 816-21.
41. Jorasch, P. Potential, Challenges, and Threats for the Application of New Breeding Techniques by the Private Plant Breeding Sector in the EU. Front Plant Sci. 2020, 11, 582011.
42. Jouanin, A., Gilissen, L.J.W.J., Schaart, J.G., Leigh, F.J., Cockram, J., Wallington, E.J., Boyd, L.A., van den Broeck, H.C., van der Meer, I.M., America, A.H.P., Visser, R.G.F., Smulders, M.J.M. CRISPR/Cas9 gene editing of gluten in wheat to reduce gluten content and exposure - reviewing methods to screen for coeliac safety. Front. Nutr. 2020, 7, 51.
43. Kalaitzandonakes, N., Willig, C., Zahringer, K. The economics and policy of genome editing in crop improvement. Plant Genome. 2023, 16(2), e20248.
44. Kamle, M., Kumar, P., Patra, J.K., Bajpai, V.K. Current perspectives on genetically modified crops and detection methods. 3 Biotech. 2017, 7(3), 219.
45. Kan, J., Cai, Y., Cheng, C., Chen, S., Jiang, C., He, Z., Yang, P. CRISPR/Cas9- guided knockout of eIF4E improves wheat yellow mosaic virus resistance without yield penalty. Plant Biotechnol. J. 2023, 21, 893–895.

46. Kapusta, J., Modelska, A., Figlerowicz, M., Pniewski, T., Letellier, M., Lisowa, O., Yusibov, V., Koprowski, H., Plucienniczak, A., Legocki, A.B. A plant-derived edible vaccine against hepatitis B virus. FASEB J. 1999, 13(13), 1796-9.
47. Karlson, D. et al. Targeted Mutagenesis of the Multicopy Myrosinase Gene Family in Allotetraploid Brassica juncea Reduces Pungency in Fresh Leaves across Environments. Plants, 2022, 11(19), 2494. Available at: https://doi.org/10.3390/plants11192494.
48. Kieu, N.P., Lenman, M., Wang, E.S., Petersen, B.L., Andreasson, E. Mutations introduced in susceptibility genes through CRISPR/Cas9 genome editing confer increased late blight resistance in potatoes. Sci. Rep. 2021, 11:4487. doi: 10.1038/s41598-021-83972-w.
49. Kondo, K., Taguchi, C. Japanese Regulatory Framework and Approach for Genome-edited Foods Based on Latest Scientific Findings. Food Saf. Tokyo Jpn. 2022, 10(4), 113–128.
50. Lanigan, T.M., Kopera, H.C., Saunders, T.L. Principles of Genetic Engineering. Genes (Basel). 2020, 11(3), 291.
51. Lemmon, Z.H., Reem, N.T., Dalrymple, J., Soyk, S., Swartwood, K.E., Rodriguez-Leal, D., Van Eck, J., Lippman, Z.B. Rapid improvement of domestication traits in an orphan crop by genome editing. Nat. Plants. 2018, 4, 766–770.
52. Li, R., Li, R., Li, X., Fu, D., Zhu, B., Tian, H. et al. Multiplexed CRISPR/Cas9-mediated metabolic engineering of γ-aminobutyric acid levels in Solanum lycopersicum. Plant Biotechnol. J. 2018, 16 415–427. 10.1111/pbi.12781.
53. Li, T., Yang, Y., Qi, H. et al. CRISPR/Cas9 therapeutics: progress and prospects. Sig. Transduct. Target. Ther. 2023, 8, 36.
54. Liang, J., Yang, X., Jiao, Y., Wang, D., Zhao, Q., Sun, Y., Li, Y., Wu, K. The evolution of China's regulation of agricultural biotechnology. aBIOTECH. 2022, 3(4), 237-249.
55. Liu, X., Zheng, J., Ding, J., Wu, J., Zuo, F., Zhang, G. When livestock genomes meet third-generation sequencing technology: from opportunities to applications. Genes (Basel). 2024, 15(2), 245.
56. Liu, D., Yang, H., Zhang, Z., Chen, Q., Guo, W., Rossi, V., Xin, M., Du, J., Hu, Z., Liu, J. An elite γ-gliadin allele improves end-use quality in wheat. New Phytol. 2023, 239 (1), 87–101.
57. Long, L., Guo, D.D., Gao, W., Yang, W.W., Hou, L.P., Ma, X.N., Miao, Y.C., Botella, J.R., Song, C.P. Optimization of CRISPR/Cas9 genome editing in cotton by improved sgRNA expression. Plant Methods. 2018, 14, 85.
58. Lu, K., Wu, B., Wang, J., Zhu, W., Nie, H., Qian, J., Huang, W., Fang, Z. Blocking Amino acid transporter Os AAP3 improves grain yield by promoting outgrowth buds and increasing tiller number in rice. Plant Biotechnol. J. 2018, 16:1710–1722. doi: 10.1111/pbi.12907.
59. Ma, J., Chen, J., Wang, M., Ren, Y., Wang, S., Lei, C., Cheng, Z. Sodmergen Disruption of OsSEC3A increases the content of salicylic acid and induces plant defense responses in rice. J. Exp. Bot. 2018, 69:1051–1064. doi: 10.1093/jxb/erx458.
60. Ma, X., Feng, F., Zhang, Y., Elesawi, I.E., Xu, K., Li, T., Mei, H., Liu, H., Gao, N., Chen, C., et al. A novel rice grain size gene OsSNB was identified by genome-wide association study in natural population. PLoS Genet. 2019, 15:e1008191. doi: 10.1371/journal.pgen.1008191.
61. Mackon, E., Jeazet Dongho Epse Mackon, G.C., Guo, Y., Ma, Y., Yao, Y., Liu, P. Development and application of CRISPR/Cas9 to improve anthocyanin pigmentation in plants: opportunities and perspectives. Plant Sci. 2023, 333, 111746.
62. Maher, E.A. Ethical and intellectual property in the biological sciences. Cell Mol. Biol. (Noisy-le-grand). 1997, 43(3),263-7.
63. Maioli, A., Gianoglio, S., Moglia, A., Acquadro, A., Valentino, D., Milani, AM., Prohen, S.J., Orzaez, D., Granell, A., Lanteri, S., Comino, C. Simultaneous CRISPR/Cas9 Editing of Three PPO Genes Reduces Fruit Flesh Browning in Solanum melongena L. Front. Plant Sci. 2020, 11:607161. doi: 10.3389/fpls.2020.607161.
64. Malnoy, M., Viola, R., Jung, M.H., Koo, O.J., Kim, S., Kim, J.S., Velasco, R., Nagamangala, K.C. DNA-Free Genetically Edited Grapevine and Apple Protoplast Using CRISPR/Cas9 Ribonucleoproteins. Front. Plant Sci. 2016, 7:1904. doi: 10.3389/fpls.2016.01904.
65. Massel, K., Lam, Y., Wong, A.C.S., Hickey, L.T., Borrell, A.K., Godwin, I.D. Hotter, drier, CRISPR: The latest edit on climate change. Theor. Appl. Genet. 2021, 134, 1691–1709.
66. Miao, C., Xiao, L., Hua, K., Zou, C., Zhao, Y., Bressan, R.A., Zhu, J.K. Mutations in a subfamily of abscisic acid receptor genes promote rice growth and productivity. Proc. Natl. Acad. Sci. USA. 2018, 4:774. doi: 10.1073/pnas.1804774115.
67. Mishra, R., Mohanty, J.N., Mahanty, B., Joshi, R.K. A single transcript CRISPR/Cas9 mediated mutagenesis of CaERF28 confers anthracnose resistance in chilli pepper (Capsicum annuum L.) Planta. 2021, 254:5. doi: 10.1007/s00425-021-03660-x.
68. Murphy, E., Walsh, P.P., Murphy, E. Nation-based peer assessment of Europe's Sustainable Development Goal performance. PLoS One. 2023, 18(6), e0287771.
69. Naeem, M., Majeed, S., Hoque, M.Z., Ahmad, I. Latest developed strategies to minimize the off-target effects in CRISPR-Cas-mediated genome editing. Cells. 2020, 9(7), 1608.
70. Ndudzo, A., Sibanda Makuvise, A., Moyo, S., Bobo, E.D. CRISPR-Cas9 genome editing in crop breeding for climate change resilience: Implications for smallholder farmers in Africa. J. Agric. Food Res. 2024, 16, 101132.
71. Ni, W., Qiao, J., Hu, S., et al. (2014). Efficient gene knockout in goats using CRISPR/Cas9 system. PLoS One. 9(9): e106718.
72. Ochoa, J.C., Mukhopadhyay, S., Bieluszewski, T., Jędryczka, M., Malinowski, R., William Truman, W. Natural variation in Arabidopsis responses to Plasmodiophora brassicae reveals an essential role for Resistance to Plasmodiophora brassicae 1 (RPB1). The Plant Journal. 2023, 116, 1421–1440 doi: 10.1111/tpj.16438.
73. Oliva, R., Ji C., Atienza-Grande, G., Huguet-Tapia, J.C., Perez-Quintero, A., Li, T., Eom, J.S., Li, C., Nguyen, H., Liu, B., et al. Broad-spectrum resistance to bacterial blight in rice using genome editing. Nat. Biotechnol. 2019, 37:1344–1350. doi: 10.1038/s41587-019-0267-z.
74. Ordonio, R.L., Baranda, E.J.G., Ii, P.J.B., Villareal, R.L. A review of new plant breeding techniques (NBTs) from the viewpoint of regulation. Monograph. 2023. Accessed: Oct. 16, 2025. Available online: https://ideas.repec.org/b/sag/semono/2023539.html.
75. Podevin, N., Devos, Y., Davies, H.V., Nielsen, K.M. Transgenic or not? No simple answer! New biotechnology-based plant breeding techniques and the regulatory landscape. EMBO Rep. 2012, 13(12), 1057-61.
76. Popova, J., Bets, V., Kozhevnikova, E. Perspectives in genome-editing techniques for livestock. Anim. Open Access J. MDPI 2023, 13, 2580.
77. Rai, G.K., Khanday, D.M., Kumar, P., Magotra, I., Choudhary, S.M., Kosser, R., Kalunke, R., Giordano, M., Corrado, G., Rou-

phael, Y., Pandey, S. Enhancing Crop Resilience to Drought Stress through CRISPR-Cas9 Genome Editing. Plants (Basel). 2023, 12(12), 2306.
78. Redman, M., King, A., Watson, C., King, D. What is CRISPR/Cas9? Arch. Dis. Child Educ. Pract. Ed. 2016, 101(4), 213–215.
79. Richael, C.M. Development of the genetically modified Innate® potato. W Goldman I. (ed.) Plant Breeding Reviews, vol. 44, pp. 57–78. John Wiley & Sons Inc., 2021.
80. Roca, M.M., Falck-Zepeda, J., Paes-Andrade, P. Cisgenics and genome editing or second generation biotechnologies: a Latin America and Caribbean perspective. W Chaurasia, A., Kole, C. (eds.) Cisgenic Crops: Safety, Legal and Social Issues, Concepts and Strategies in Plant Sciences. Springer, Cham, 2023.
81. Rzymski, P., Królczyk, A. Attitudes toward genetically modified organisms in Poland: to GMO or not to GMO? Food Sec. 2016, 8, 689–697.
82. Sánchez-León, S., Gil-Humanes, J., Ozuna, C.V., Giménez, M.J., Sousa, C., Voytas, D.F., Barro, F. Low-gluten, nontransgenic wheat engineered with CRISPR/Cas9. Plant Biotechnol. J. 2018, 16:902–910. doi: 10.1111/pbi.12837.
83. Shan, Q., Zhang, Y., Chen, K., Zhang, K., Gao, C. Creation of fragrant rice by targeted knockout of the OsBADH2 gene using TALEN technology. Plant Biotechnol. J. 2015, 13:791–800. doi: 10.1111/pbi.12312.
84. Shan, Q., Zhang, Y., Chen, K., Zhang, K., Gao, C. Creation of fragrant rice by targeted knockout of the OsBADH2 gene using TALEN technology. Plant Biotechnol. J. 2015, 13:791–800. doi: 10.1111/pbi.12312.
85. Shew, A.M., Nalley, L.L., Snell, H.A., Nayga, R.M., Dixon, B.L. CRISPR versus GMOs: public acceptance and valuation. Global Food Security. 2018, 19, 71–80.
86. Shokravi, H., Shokravi, Z., Heidarrezaei, M., Ong, H.C., Koloor, S.S.R., Petrů, M., Lau, W.J., Ismail, A.F. Fourth generation biofuel from genetically modified algal biomass: Challenges and future directions. Chemosphere. 2021, 285, 131535.
87. Shou, H. CRISPR/Cas9-Mediated Knockout of GmFATB1 Significantly Reduced the Amount of Saturated Fatty Acids in Soybean Seeds. Int. J. Mol. Sci. 2021, 22:3877. doi: 10.3390/ijms22083877.
88. Singh, S., Rahangdale, S., Pandita, S., Saxena, G., Upadhyay, S.K., Mishra, G., Verma P.C. CRISPR/Cas9 for insect pests management: A comprehensive review of advances and applications. Agriculture. 2022, 12(11), 1896.
89. Smyth, S.J. The state of genetically modified crop regulation in Canada. GM Crops Food. 2014, 5(3), 195-203.
90. Sun, M., Li, S., Yang, W., Zhao, B., Wang, Y., Liu, X. Commercial genetically modified corn and soybean are poised following pilot planting in China. Mol. Plant 2024, 17(4), 519–521.
91. Szopa, J., Kulma, A. Improving the growth and bioactive compound production of selected plant species using controlled genetic and epigenetic manipulation. Acta Soc. Bot. Pol. 2022, 91, 9120.
92. Tachikawa, M., Matsuo, M. Global regulatory trends of genome editing technology in agriculture and food. Breed Sci. 2024, 74(1), 3-10.
93. Thygesen, P. Regulation of genome edited organisms in Australia. Transgenic Res. 2024, 33(6), 545-550.
94. Tim, U. et al. Low Fiber Pennycress Meal And Methods Of Making. US. 2018. Available at: https://lens.org/046-467-999-135-312.
95. Tsatsakis, A.M., Nawaz, M.A., Tutelyan, V.A., Golokhvast, K.S., Kalantzi, O.I., Chung, D.H., Kang, S.J., Coleman, M.D., Tyshko, N., Yang, S.H., Chung, G. Impact on environment, ecosystem, diversity and health from culturing and using GMOs as feed and food. Food Chem. Toxicol. 2017, 107(Part A), 108–121.
96. United Nations, Department of Economic and Social Affairs. Transforming our world: the 2030 Agenda for Sustainable Development. Accessed: 16 October 2025. Available online: https://sdgs.un.org/2030agenda.
97. USDA. Coordinated Framework for Regulation of Biotechnology. Accessed: 23 October 2025. Available online: https://www.aphis.usda.gov/sites/default/files/coordinated_framework.pdf.
98. Villiger, L., Joung, J., Koblan, L., Weissman, J., Abudayyeh, O.O., Gootenberg, J.S. CRISPR technologies for genome, epigenome and transcriptome editing. Nat. Rev. Mol. Cell Biol. 2024, 25(6), 464–487.
99. Waltz, E. Gene-edited CRISPR mushroom escapes US regulation. Nature. 2016, 532(7599), 293.
100. Waltz, E. Gene-edited CRISPR mushroom escapes US regulation. Nature 532, 293 (2016). https://doi.org/10.1038/nature.2016.19754
101. Waltz, E. With a free pass, CRISPR-edited plants reach market in record time. Nat. Biotechnol. 2018, 36(1), 6–7. Available at: https://doi.org/10.1038/nbt0118-6b.
102. Wang, Y., Cheng, X., Shan, Q., Zhang, Y., Liu, J., Gao, C., Qiu, J.L. Simultaneous editing of three homoeoalleles in hexaploid bread wheat confers heritable resistance to powdery mildew. Nat Biotechnol. 2014, 32(9), 947-51.
103. Wang, Y., Cheng, X., Shan, Q., Zhang, Y., Liu, J., Gao, C., Qiu, J.L. Simultaneous editing of three homoeoalleles in hexaploid bread wheat confers heritable resistance to powdery mildew. Nat. Biotechnol. 2014, 32:947–951. doi: 10.1038/nbt.2969.
104. Watson, O., Hayta, S., Precision breeding in agriculture and food systems in the United Kingdom. Transgenic Res. 2024, 33(6), 539-544.
105. Watson, E. Tropic to launch non-browning bananas in March, extended shelf-life bananas by year-end, AgFunderNews, 21 February 2025. Available at: https://agfundernews.com/tropic-to-launch-non-browning-bananas-in-march-extended-shelf-life-bananas-by-year-end (Accessed: 27 November 2025).
106. Wu, N., Lu, Q., Wang, P., Zhang, Q., Zhang, J., Qu, J., Wang, N. Construction and Analysis of GmFAD2-1A and GmFAD2-2A Soybean Fatty Acid Desaturase Mutants Based on CRISPR/Cas9 Technology. Int. J. Mol. Sci. 2020, 21(3), 1104.
107. Xu, R., Yang, Y., Qin, R., Hao, L., Qiu, C., Li, L., Wei P. Rapid improvement of grain weight via highly efficient CRISPR/Cas9-mediated multiplex genome editing in rice. J. Genet. Genom. 2016, 43:529–532. doi: 10.1016/j.jgg.2016.07.003.
108. Zaman, Q.U., Ilyas, M., Aamer, M., Batool, M., Li, H., Wu, Z. A Critical Review: Recent Advancements in the Use of CRISPR/Cas9 Technology to Enhance Crops and Alleviate Global Food Crises. Curr. Issues Mol. Biol. 2021, 43(3), 1950-1976.
109. Zarate, S., Cimadori, I., Jones, M.S., Roca, M.M., Barnhill-Dilling, S.K. Assessing agricultural gene editing regulation in Latin America: an analysis of how policy windows and policy entrepreneurs shape agricultural gene editing regulatory regimes. Front. Bioeng. Biotechnol. 2023, 11, 1209308.
110. Zhang, Y., Li, D., Zhang, D., Zhao, X., Wang, D. Analysis of the functions of TaGW2 homoeologs in wheat grain weight and

protein content traits. Plant J. Cell Mol. Biol. 2018, 94:857–866. doi: 10.1111/tpj.13903.

111. Zhang, Y., Liang, Z., Zong, Y., Wang, Y., Liu, J., Chen, K., Qiu, J.L., Gao, C. Efficient and transgene-free genome editing in wheat through transient expression of CRISPR/Cas9 DNA or RNA. Nat. Commun. 2016, 7:12617. doi: 10.1038/ncomms12617.
112. Zhao, Z., Shang, P., Mohanraju, P., Geijsen, N. Prime editing: advances and therapeutic applications. Trends Biotechnol. 2023, 41, 1000–1012.
113. Zhao, D.S., Li, Q.F., Zhang, C.Q., Zhang, C., Yang, Q.Q., Pan, L.X., Ren, X.Y., Lu, J., Gu, M.H., Liu, Q.Q. GS9 acts as a transcriptional activator to regulate rice grain shape and appearance quality. Nat. Commun. 2018, 9(1), 1240.
114. Zhou, W., Wan, Y., Guo, R., Deng, M., Deng, K., Wang, Z., Zhang, Y., Wang, F. Generation of Beta-Lactoglobulin Knockout Goats Using CRISPR/Cas9. PLoS ONE 2017, 12, e0186056.
115. Zhu, H., Li, C., Gao, C. Publisher Correction: Applications of CRISPR-Cas in agriculture and plant biotechnology. Nat. Rev. Mol. Cell Biol. 2020, 21:712. doi: 10.1038/s41580-020-00304-y.
116. Zhu, Y., Lin, Y., Chen, S., Liu, H., Chen, Z., Fan, M., Hu, T., Mei, F., Chen, J., Chen, L., Wang, F. CRISPR/Cas9-mediated functional recovery of the recessive rc allele to develop red rice. Plant Biotechnol. J. 2019, 17 (11), 2096–2105.