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Review

Precision harvest: path to genetically modified organism-free crops with CRISPR by 2035

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Recent advances in clustered regularly interspaced short palindromic repeats (CRISPR) technology enable precise genetic modifications and produce genetically modified organism -free crops that match consumer preferences. By 2035, we will be able to consume CRISPR-edited crops, addressing food security issues and boosting economies for individual countries. This review highlights the progress of genetically modified crops and the regulatory challenges involved in bringing CRISPR-edited crops to market based on product- and process-based approaches across different regions. We also examine public preferences regarding these technologies and the current status of CRISPR-edited crops in terms of market availability. Furthermore, we stress the importance of establishing clear safety standards, effective patent management, and guidance on regulatory pathways for crop approval, as well as exploring future directions for integrating these technologies with artificial intelligence.

The evolution of genetically modified organism crops

For thousands of years, people have tried to improve crops, livestock, and the food we consume through selective breeding. However, the 20th century marked a significant turning point with the introduction of genetically modified organisms (GMOs), developed through gene technology to achieve desirable traits in crop species, such as increased yield, nutrient composition, and food quality; enhanced resistance to insect pests; and improved food security and medicinal benefits, which are especially important for a growing global population [1]. The first wave of genetically modified (GM) crops (soybeans, cotton, corn, papayas, tomatoes, potatoes, and canola) was developed in the mid-1990s. However, these are not immediately available because of the need to meet regulatory and safety standards similar to those derived from traditional breeding. The GM Flavr Savr tomato, approved for commercial production in 1994, was the first GM crop to reach the market [2]. Since then, the list of GM crops has continued to expand, including insect-resistant Bt cotton, herbicide-tolerant soybeans, and golden rice, among others (Figure 1). As of today, they are cultivated across 208.9 million hectares worldwide, including the largest producers of GM crops: the USA, Brazil, Argentina, Canada, and India[i]. Moreover, GMO crops have generated a market value of $23.41 billion through efforts that spanned more than 30 years. It is projected that market demand will continue to grow with a compound annual growth rate (CAGR) of 6.9%, reaching approximately $48.28 billion by 2035[i,ii] (Figure 2). Considering the importance of GM crops, it is also essential to take public perception into account regarding their use and their long-term effects associated with health and other side effects. For example, some countries, such as European nations and New Zealand, focus on the process used to create a crop (regulating any use of biotech methods as a GMO and requiring proper labeling).

Highlights

Clustered regularly interspaced short palindromic repeats (CRISPR)-edited crops attain genetically modified organism (GMO)-free status in several jurisdictions, circumventing traditional regulatory obstacles.

First-generation CRISPR crops enter commercial markets, showing practical viability and consumer acceptance.

Post-transcriptional editing techniques enable accurate regulation of gene expression without inserting foreign DNA.

Regulatory divergence establishes new paradigms that differentiate precision breeding from conventional genetic modification.

Recent consumer studies show increased acceptance of gene editing compared to traditional GMOs.

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In contrast to this, in countries such as the USA, the focus is on the product characteristics (regulating only if the end product has novel risks or traits) [3]. Additionally, experts have raised ecological concerns regarding the use of GMOs, including the unintended introduction of modified genes into wild relatives or traditional crop varieties. For example, such gene flow may contribute to the emergence of herbicide-resistant weeds (often referred to as superweeds), which are almost impossible to handle in the field. Moreover, the increased risk of cross-contamination between GM and non-GM crops may lead to a loss of biodiversity and negatively affect the profitability of non-GM varieties, especially in markets that demand strict genetic purity[iii]. The solution to these challenges is to design GM crops that do not rely on transgenic modifications. In the era of the modern world and significant advancements in precision breeding technologies, especially with the discovery of clustered regularly interspaced short palindromic repeats (CRISPR) and their associated proteins, there is a promising opportunity for generating GMO-free crops, which could help to meet food security demands and also improve nutritional quality, as well as reduce ecological risks [4–6].

The CRISPR/Cas9 system operates through a guide RNA directing the Cas9 nuclease to a specific DNA locus, inducing a double-strand break. Cellular repair via nonhomologous end joining often disrupts gene function and achieves knockout, typically introducing small insertions or deletions (indels) that can occur naturally or through conventional mutagenesis. Moreover, the CRISPR/Cas9 system allows precise modifications of a plant's DNA without introducing foreign genes from noncrossable species [7]. In this context, if a gene-edited plant is substantially equivalent to a conventionally bred plant, many scientists and regulatory agencies argue that it may not require special premarket approval, since no novel genes from unrelated organisms are present. CRISPR-edited crops are already available in the market, such as GABA tomatoes [8], white button mushrooms, soybeans, and mustard greens[iv] [9]. Moreover, CRISPR-edited crops are already undergoing field trials, such as high-yielding and stress-tolerant rice in India, China, and Italy[v,vi,vii], as well as low-gluten wheat field trials in the EU [10].

CRISPR-edited crops: ready to hit the market

The CRISPR-based gene-editing toolbox enables multidimensional, high-throughput genome editing and manipulation [11]. Since its introduction to plant systems in 2013, this technology has been successfully applied to a wide range of crops, resulting in improved yield, quality, and resilience to stress. Scientists estimate that we will be able to consume CRISPR-edited crops within the next 10 years, as most are currently undergoing approval processes to enter the market (Table 1) [26]. The practical application value of gene editing shows greater potential

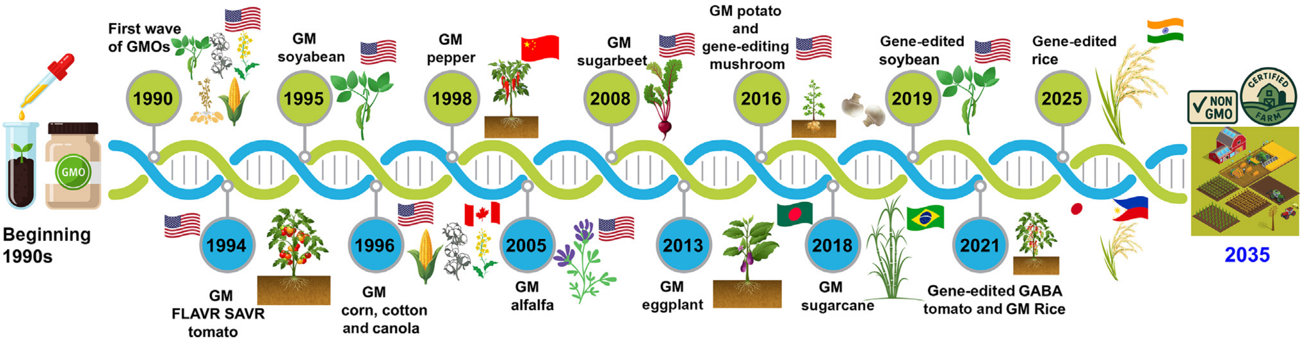

Figure 1. Evaluation of GM crops: timeline of key milestones in the development of GM crops from the 1990s toward 2035 to achieve non-GM crops. GM: genetically modified; GMO: genetically modified organism.

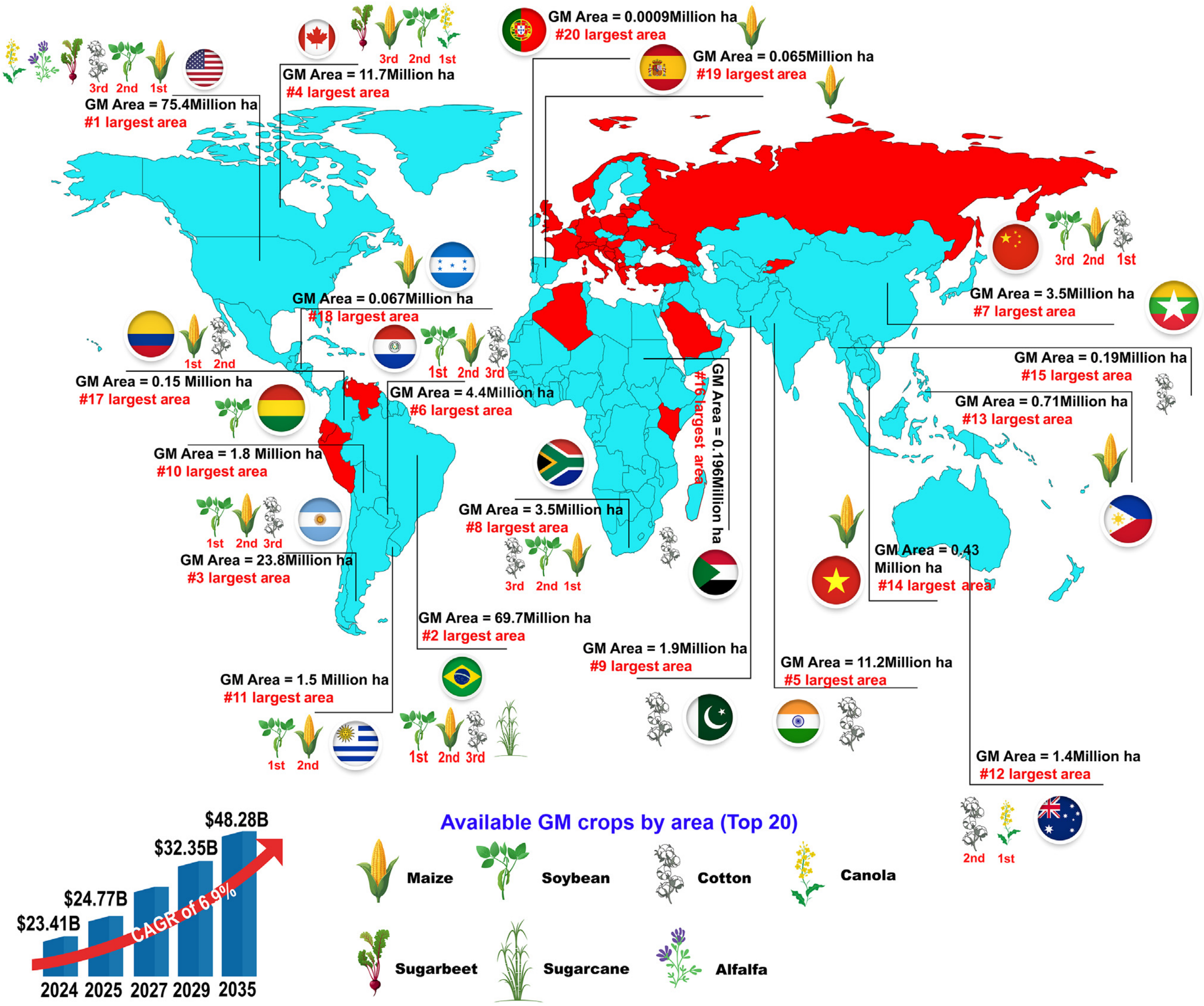

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Figure 2. Global distribution of GM crops and their international ranking based on each country's cultivated area as of 2024. Icons indicate specific GM crop types cultivated in each country. Additionally, the inset bar graph projects the economic market growth of GM crops from 2024 to 2035, showing a CAGR of 6.9%. CAGR: compound annual growth rate; GM: genetically modified.

compared to traditional genetic modification approaches. Unlike conventional GMOs, CRISPR-edited crops can bypass many regulatory hurdles and gain easier public acceptance, making gene editing a practical pathway to achieving GMO-free crop improvement.

Another key frontier for CRISPR/Cas9 is the manipulation of post-transcriptional regulatory mechanisms that govern mRNA processing, stability, localization, and translation. Ferreira and Reis (2023) emphasize the enhancement of gene expression by editing sequences involved in post-transcriptional repression, a shift from CRISPR/Cas9's conventional role in gene silencing [27]. Editing regulatory elements within untranslated regions (UTRs) is one such strategy. CRISPR-mediated editing or removal of uORF start codons, or the introduction of premature stop codons within the uORF, has effectively enhanced main ORF translation. This was

Table 1. Examples of upcoming CRISPR-edited crops

Crop	Gene name	Gene ID	Modified traits	Status	Refs
Groundcherry tomato	*CLAVATA1 and SELF-PRUNING*	*Ppr-CLV1* and *Ppr-SP*	Plant architecture, flower production, and fruit size	Research completed and ready for market	[12]
Wild tomato	*SELF-PRUNING, OVATE, FRUIT WEIGHT-2.2*, and *LYCOPENE BETA CYCLASE*	*SP, O, FW2.2*, and *CycB*	Increased number and size of fruit and higher nutritional content	Research completed and in field trials' stages	[13]
White button mushroom	*Polyphenol oxidase*	*PPO*	Prevent from browning and increase shelf life	Ready for market and unregulated by USDA and waiting for FDA approval	[14]
Rice	*Pyrabactin* resistance family	*PYR family*	Higher grain yield	Research continued	[15]
Wheat	*α-gliadins*	*α-gld*	Low-gluten wheat	Research completed and in field trials' stages	[16]
Cabbage	*Photosystem II Subunit S*	*PsbS*	Improve growing patterns	Research completed and waiting for EU ruling	[17]
Soybean	*Acetolactate synthase1* and *two genomic sites*	*DD20*, *DD43*, and *ALS1*	Drought tolerance, seed oil composition improvement, and herbicide tolerance	Successfully achieved proof of concept	[18]
Potatoes	*Granule-bound starch synthase genes*	*GBSS*	Long shelf life and prevent from browning	Successfully achieved proof of concept	[19]
Cotton	*Phytoene desaturase, elongation factor 1*, and *Chloroplasts alterados 1*	*GhPDS*, *GhCLA1*, and *GhEF1*	Albino seedlings, nutritional content and disease resistance, and overall plant productivity	Successfully achieved proof of concept	[20]
Canola	*REPRESSOR OF GA1-3*, *FRUITFULL*, and *LARGE IN CHINESE*	*BnaRGA*, *BnaFUL*, and *BnaDA*	Improve shatter resistance and yield losses	Successfully achieved proof of concept	[21]
Casava	*Eukaryotic translation initiation factor 4E*	*eIF4E*	Resistance to CBSV, higher yield, and produce a waxy, starch-like substance	Successfully achieved proof of concept	[22]
Mustard	Type-I *myrosinase*	Multiple genes	Reduce in pungency	Research completed and in field trials' stages	[23]
Waxy corn	*Waxy* allele	Waxy genes	Higher yield	Research completed and ready for market	[24]
Soybean	Double-stranded *RNA-binding protein 2*	*Drb2a and Drb2b*	Drought and salt tolerance	Research completed, unregulated by USDA, and waiting for FDA approval	[4]
Waxy corn	*Waxy* gene	*Wx1*	High starch content	Approved and ready for market	[25]

CBSV: Cassava Brown Streak Virus.

demonstrated by improving ascorbate content in lettuce through targeting the uORF of *GDP-L-galactose phosphorylase* (*LsGGP2*) [28] and increasing sweetness in strawberries by editing uORFs in genes related to sugar metabolism [29]. Similar strategies are being explored in staple crops, such as rice and maize, to enhance the translation of stress-responsive or yield-related proteins [30].

Another strategy is miRNA editing, which involves ~21-nucleotide small noncoding RNAs that post-transcriptionally regulate gene expression by binding to complementary sequences in target mRNAs, typically leading to their cleavage or translational repression [31]. Editing miRNA target sites within specific genes offers a precise method to release these genes from miRNA-mediated suppression, thereby enhancing their expression and influencing desired traits—a promising approach, given the evolutionary conservation of miRNAs and their targets, which aids technique transfer from model organisms to crops [32]. Targeting miR156 binding sites in

SQUAMOSA PROMOTER BINDING PROTEIN-LIKE (*SPL*) genes has been applied in various crops. In rice, disrupting miR156 binding to *OsSPL14, Ideal Plant Architecture 1*, led to increased tiller number and panicle size [33]. Editing specific miRNA target sites is advantageous over deleting miRNA genes, as the latter can cause pleiotropic effects from the nonspecific derepression of all miRNA targets [1]. For example, in-frame deletion of the miR396 target site in rice *GROWTH REGULATING FACTOR 4* (*OsGRF4*) and *OsGRF8* enhanced transcript stability, yielding larger grains and improved brown planthopper resistance, respectively [32]. Editing target sites in UTRs, such as the miR156 site in the 3′-UTR of wheat's *TaSPL13* gene, which improved yield components, offers greater flexibility due to reduced constraint on the coding sequence [34]. Multiplex editing of several miRNA target sites simultaneously, or even the miRNA genes themselves (e.g., knocking out specific members of a large miRNA family), is also becoming feasible to modulate complex traits.

CRISPR/Cas9 can also be used to modulate protein function via post-translational modifications (PTMs), for instance. PTMs like phosphorylation, ubiquitination, SUMOylation, glycosylation, and acetylation significantly diversify proteome function, affecting protein activity, stability, subcellular localization, and interactions. Precise gene editing to modulate PTM sites has the potential to alter protein conformation, accessibility of PTM sites, or domains involved in PTM-mediated regulation—a largely untapped gene-editing approach in crop improvement [35]. The following are a few successful examples of CRISPR-edited crops demonstrating market readiness. A nonbrowning white button mushroom was created by knocking out one of six *polyphenol oxidase (PPO)* genes and is already available in the US market [14]. CRISPR-edited waxy corn is already available in the market in several countries as a GMO-free crop. This variety offers improved starch quality and is produced without introducing foreign DNA, allowing it to bypass GMO classification in specific regulatory systems [24].

Groundcherry tomatoes have been edited using CRISPR to produce fewer sprawling bushes, larger fruit, and higher levels of vitamin C. They also exhibit resistance to bacterial spot disease and salt stress and adhere more effectively to their stems. These traits were achieved by editing the *SELF-PRUNING (SP)* gene, which is associated with determinate growth, and the *CLAVATA1 (CLV1)* gene, which is responsible for maintaining the meristem and promoting flower development. These tomatoes are expected to be ready for market in the coming years [12]. Similarly, high-yield *de novo* domesticated wild tomatoes have reached the field trial stage. These varieties exhibit significantly higher yields and up to 500% more fruit lycopene accumulation compared to traditional cultivars [13]. Higher-yielding rice varieties are also on the way, created through targeted mutations in a subfamily of abscisic acid receptor genes [15]. Low-gluten wheat is currently in field trial stages, having been developed through the targeted manipulation of α-gliadin genes [16]. A less pungent mustard is also in the approval stages, developed through targeted mutations in the multicopy myrosinase gene family. This modification reduces the sharpness of flavor while preserving the plant's nutritional and agronomic qualities [23]. Other upcoming CRISPR-edited crops are in various stages of approval before entering the market, as highlighted in Table 1[xvi]. In addition to this, more crops are expected to be introduced in the future, and by 2035, we will be able to incorporate a wide variety of CRISPR-edited foods into our daily diet.

Regulatory landscape: navigating non-GMO classification

A key global regulatory controversy is whether CRISPR-edited crops, especially those that do not contain foreign DNA, should be classified and regulated as GMOs or treated as non-GMOs[viii]. An increasing number of countries regulate genome editing in crops in a way different from 'classic' GMOs [36]. Argentina was a global pioneer in the regulation of gene-edited crops by introducing a policy in 2015 that exempts certain genome-edited plants from GMO oversight if they do not contain foreign DNA [36]. The USA and Canada have historically employed a product-based regulatory approach. This means that biotech crops are regulated under existing laws based on their characteristics, such as pest risk or food safety considerations (Figure 3). If a gene-edited plant is deemed substantially equivalent to a conventionally bred plant, it may not need special premarket approval[ix]. Several other countries, including Brazil, Chile, Japan, and Australia, have implemented similar regulatory frameworks that differentiate between traditional GM and gene-edited GM crops[viii,ix]. In contrast, the EU historically exemplifies a process-based regulatory philosophy, and GMO laws regulate organisms based on the use of genetic engineering techniques. For example, under EU rules[x], even a minor genome edit can render a plant a regulated GMO [37].

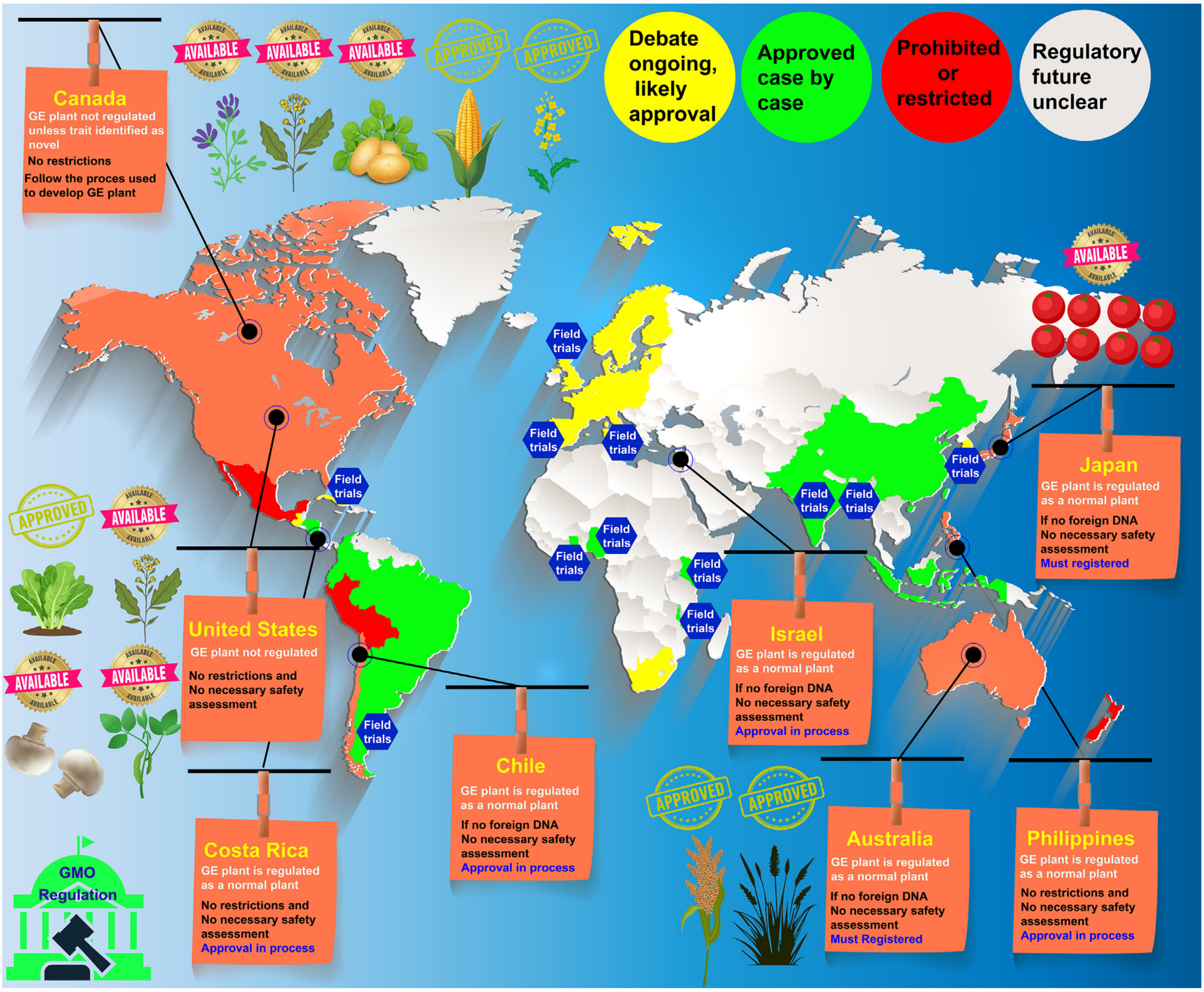

Figure 3. Global regulation of GE plants. The world map shows the status of GE plant approval and regulation across different countries. Various regions are color-coded according to their regulatory status. The information bar indicates countries, where GE plants are approved and available. Other countries are marked with circles in the corners. Additionally, countries with ongoing CRISPR-edited crop field trials are indicated by blue dots. More advanced editing is still subject to full GMO procedures, and product safety is overseen by a separate authority, FSANZ. CRISPR: clustered regularly interspaced short palindromic repeats; GMO: genetically modified organism.

In 2024, the FDA reaffirmed its 'risk-based approach' for genome-edited plant foods, issuing guidance for developers to engage with the agency early. Depending on the crop's characteristics, developers can have 'voluntary premarket consultations' or expedited 'voluntary premarket meetings' with the FDA to ensure all safety questions are addressed. Foods from genome-edited plants must meet the exact requirements of other foods[xi]. In January 2022, Chinese regulators published guidelines for the trial of gene-edited plants, outlining a streamlined approval process for such trials. Under these draft rules, a gene-edited crop can skip some of the lengthy steps required for transgenic GMOs. In practice, this could shorten approval time from ~6 years (for a GMO) down to 1–2 years for a gene-edited crop. China's regulatory shift toward GE crops presents both an opportunity and a challenge [38]. The UK moved quickly to diverge from EU GMO rules, and gene-edited crops with no foreign genes can be cultivated and marketed more easily using precision-bred organism systems[xii]. In May 2022, the Canadian Food Inspection Agency clarified how this applies to gene editing. If a gene-edited plant's trait is not novel (i.e., it could be achieved through conventional breeding and is found in the species' gene pool), it may be exempt from regulation. A GMO or gene-edited crop is only regulated if the final trait is new to the species or poses a greater risk [xiii]. However, some countries (e.g., New Zealand) continue to maintain purely process-based lines, which effectively block or slow the domestic use of CRISPR in crops.

Globally, the regulatory trend is moving toward more nuanced, science-based frameworks that distinguish between different types of genetic modifications, with an increasing recognition that CRISPR-edited crops without foreign DNA warrant differentiated regulatory treatment from traditional GMOs. However, it is worth noting that regulatory divergence poses challenges for international trade, as asynchronous approvals can lead to disruptions. Strict process-based regulation contrasts with the flexible product-based approaches, which risks trade conflicts [39].

Policy fragmentation, trade barriers, and low institutional trust each limit the market for the entry of gene-edited crops. When countries apply different rules or approve products at different times, as seen with GM maize and soy, trade becomes disrupted, and companies face higher costs for segregation, which reduces incentives to release new traits in the markets [39]. The same type of regulatory mismatch would restrict gene-edited crops to domestic markets even when scientific assessments show low risk. Trade barriers get worse, because exporters risk refusal if importing countries classify the same edit in a different way. At the same time, low trust in regulators and industry reduces willingness to consume gene-edited foods, limiting uptake, as farmers and consumers hesitate to accept products they believe are not transparently assessed [40,41]. Evidence from early adopters of gene-edited foods/crops, such as Canada and China, shows that clear product-based regulations, open access to safety data, and early public engagement help move gene-edited crops from approval to actual use [36,37,42]. Regulatory coordination and transparent governance, therefore, provide practical ways to reduce fragmentation, manage trade risks, and build trust.

Public perception and consumer acceptance

Gene-editing technologies using CRISPR/Cas in crop plants are expected to gain more acceptance among the public. This expectation is based on the fact that most applications will not differ from the results produced by traditional mutagenesis methods that use chemicals or radiation. Although the crop plants will initially contain a temporary transgenic component, they will ultimately be free from transgenes and will solely inherit the induced mutation. In contrast to radiation and chemical mutagenesis, this aim is achieved more swiftly and with greater precision. While many people lack an understanding of the technology, it holds significant meaning for everyone. A 2023 US study [43] showed that gene editing consistently achieves higher favorability in both social and traditional media. The authors presented the findings of a five-year study (2018–2022), clearly indicating that gene editing in agricultural biotechnology enjoys a high level of acceptance [43]. Over several months, particularly on social media, all reports demonstrate a 100% positive tendency, further supported by traditional media reports. During the same period, articles about GMOs in conventional media were consistently 10–20% less favorable compared to those on gene editing. Based on their findings, we can be cautiously optimistic that the public will accept gene editing and that it can fulfill its promise of making a substantial contribution to future food security and environmental sustainability. Another study involved 3700 individuals from five countries (Canada, USA, Austria, Germany, and Italy). They faced the challenge of applying gene editing to introduce disease resistance in humans, plants, and animals [44]. Participants were presented with one of the five applications and asked to determine whether they considered it right or wrong. Participants in all countries categorically stated that applying disease resistance in humans is the most crucial area to pursue, followed by disease resistance in plants and subsequently in animals. They unequivocally regarded changes in product quality and quantity. However, participants from the USA and Italy were generally more positive overall, whereas participants from Germany and Austria tended to be more negative. Cluster analyses identified four groups of participants: 'strong supporters', who saw only benefits and little risks; 'slight supporters', who perceived risks and valued benefits; 'neutrals', who exhibited no pronounced opinion; and 'opponents', who perceived higher risks and lower benefits. A UK study involving 2566 adults from UK found that 45% of respondents strongly supported the legalization of gene-edited crops[xiv]. In 2023, Research First, a research firm, conducted a national survey in New Zealand, which definitively revealed what consumers expect from their food producers. The results were precise: a third of New Zealanders favor the cultivation of GM crops in the country. Public support for gene editing in New Zealand's food production was divided, with 32% in favor, 47% neutral, and 21% against (Market Gardeners Ltd, New Zealand news, 2023). A survey of 1096 Costa Ricans revealed their attitudes, knowledge, and perceptions of gene-editing technology and crops. The survey was administered in person and consisted of three parts, comprising 26 questions. The results are precise: Costa Rican consumers are open to the application of gene editing in agriculture and would consider consuming products derived from this technology. They are receptive to using gene-editing technology to address concerns related to human and animal health. However, Costa Rican consumers are not willing to accept the use of gene editing to 'design' human traits [45]. When examining the key drivers of public sentiment, categorize them as follows: perceived benefits, transparency and availability of information, trust in institutions, and the moral and ethical context. It is evident that public acceptance increases when gene editing addresses direct benefits, such as improved nutrition, enhanced resilience, and reduced ecological impact [46]. Clear labeling, open communication about the science involved, and educational outreach foster consumer trust, which is viewed positively and enhances public acceptance. A higher level of trust in regulatory and scientific bodies correlates with greater acceptance. Studies indicate that consumer trust in scientists, regulators, and industry results in increased benefits and reduced risks, significantly enhancing purchase intent. For instance, among Vietnamese consumers, trust contributed to more positive perceptions of GM foods and a greater willingness to purchase them [47]. A survey of 2000 individuals in the USA conducted by Iowa State University revealed that a higher level of trust in the government, biotech companies, and regulators is strongly correlated with a willingness to consume gene-edited foods. Conversely, distrust—particularly among older, more religious, or female demographics—led to avoidance [40]. Regulatory leniency correlates with public confidence. In countries such as China, public trust in government and national scientific capacity plays a crucial role in the approval of gene-edited wheat varieties by the state. Trust serves as the social license for commercialization [41]. Consumer backlash can and will impede or reverse policy. In UK, opposition groups are resolute: permitting gene-edited crops will undermine 'trust in the country's reputation for natural food' and affect the SNP's hesitancy, despite the broader UK's adoption (thetimes.co.uk). Trade negotiations and regulatory alignment are undoubtedly influenced by trust. The UK's Genetic Technology Act, which seeks to deregulate gene editing, confronts resistance from the EU. Brussels requires realignment with EU regulations before market access is restored, highlighting distrust of UK policy divergence (thetimes.co.uk).

There are several proven strategies for effectively communicating and educating the public. The first is principled and deliberative engagement. Implement educational modules that allow students to discuss ethical scenarios. This will enhance understanding and raise public awareness by combining fact-based learning with group dialogue [42]. Second, focus groups and citizen juries consistently show increased acceptance by addressing perceptions of 'naturalness' compared to GMOs [48]. Another effective method for promoting outreach is through the framework for responsible research and innovation. This approach emphasizes reflective, inclusive, and iterative engagement. It encourages the public to reflect on their motivations, engage in genuine dialogue, and cocreate research directions, thereby building legitimacy and trust. The next option is science education grounded in evidence and context. Educational programs that connect CRISPR to real-world benefits, such as drought tolerance, disease resistance, and reduced antibiotic use in animals, enable students to appreciate the practical value and ethical framing. Effective public outreach is crucial for fostering scientific literacy, which includes understanding the scientific method, recognizing misinformation, and distinguishing fact from hype. Lastly, there are media-optimized messages and messengers. Replace jargon-heavy text with visual storytelling that is accessible, emotionally engaging, and relatable, particularly regarding sustainability and ethical issues. Train speakers to tailor their messages to lay audiences, thereby deepening trust. It is vital to use trusted voices—not just scientists, but also farmers, local NGOs, and religious and community leaders—to share balanced insights on the benefits and safeguards of gene editing [49].

Concluding remarks and future outlook

CRISPR-edited crops are a promising step forward in agriculture, shifting from traditional genetic modification toward precision breeding. It is hoped that with significant advancements and clear regulations on their use by 2035, food security challenges will be addressed [50,51]. However, some key issues related to CRISPR-edited crops still need resolution to achieve public market acceptance [52]. One major concern is the unclear regulatory distinction between precision breeding and genetic modification, as mentioned above. To address this, transparent safety standards and approval processes for CRISPR-edited crops and their products are essential for fostering market confidence and establishing them in public markets [53–55]. Another obstacle is the patent thicket surrounding CRISPR-edited crops. Overcoming these barriers requires licensing criteria that are straightforward and adhere to proper safety standards, potentially through international patent pools and humanitarian licensing frameworks. In this regard, public–private partnerships will play a vital role in overcoming barriers to adoption and ensuring the availability of CRISPR-edited crops [56]. It is also crucial to recognize that consumer trust is vital for the commercial success of these crops; without it, even scientifically proven the market may overlook benefits.

It is estimated that by the end of 2035, high-yielding, stress-resistant, and nutrient-efficient crops will be available for public use, helping to reduce hunger. Disease-resistant crops will decrease pesticide use, as demonstrated by various studies [57]. In contrast, nutrient-efficient crops will conserve arable land and address regional nutritional deficiencies, thereby reducing the environmental footprint of agriculture [57,58]. CRISPR-edited crops will also shape the future of personal diets as functional foods tailored to specific health needs. Furthermore, CRISPR technology will

Outstanding questions

Which clustered regularly interspaced short palindromic repeats-edited crops have been introduced to the market?

Is the value of the CRISPR/Cas technology acknowledged by the consumers?

Does CRISPR/Cas technology challenge the genetically modified organism paradigm?

Do regulatory processes consider scientific progress in the field?

play a vital role in creating more resilient food supply chains by improving postharvest traits, such as shelf life and browning resistance, which can significantly reduce food waste [5,59]. The success of these GMO-free CRISPR applications will likely catalyze a broader shift in agricultural biotechnology, potentially making CRISPR the preferred method for crop enhancement over conventional GMO technologies.

Furthermore, with the advancement and widespread use of CRISPR gene-editing technology, large amounts of data on gene-editing mutants and related information have been produced, offering crucial support for data-driven research in artificial intelligence (AI). The integration of CRISPR with AI technologies, such as large language models like CRISPR-GPT [60], Plant-GPT [61], SeedLLM and PLLaMA [62], CRISPRoffT [63], and CropGPT [64], will assist in predicting protein functions and deepen the understanding of complex gene regulatory networks. Additionally, employing these tools will aid in genomic functional studies, thereby improving targeting efficiency and reducing off-target effects in gene-editing applications [65]. The continuous development of more precise and efficient CRISPR variants (e.g., those with expanded PAM compatibility or diminished off-target activity), along with progress in high-throughput phenotyping and multiomics platforms, will speed up the discovery of new genetic targets and the creation of innovative crop improvement strategies [57,66]. The possibility of creating synthetic regulatory circuits by combining edited promoters, UTR elements, and coding sequences offers exciting opportunities for designing plants with custom traits. Moving from basic gene knockouts to sophisticated editing of regulatory sequences and protein-coding regions that control mRNA fate and protein function will unlock new levels of crop productivity, stress tolerance, and nutritional quality. This significantly advances sustainable agriculture. A broad array of regulatory mechanisms that influence the abundance and activity of nearly all molecules in living organisms provides a vast, largely unexplored potential for CRISPR/Cas9-mediated crop enhancement.

In conclusion, we need to transition from top-down science dissemination to dialogue-oriented, value-driven communication to bridge the gap in CRISPR acceptance. Interactive, open, and contextually rich education delivered by trusted voices is vital for fostering deeper engagement and acceptance of gene-edited crops (see also Outstanding questions).

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Declaration of interests

The authors declare no competing interests.

Resources

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