TRENDS IN AGRICULTURE SCIENCE
ISSN:2583-7850

Popular Article
Domain: Agriculture Science
Vol 4 Issue 9, September 2025, 5013-5018

CRISPR and the Future of Genetically Edited Crops

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DOI:10.5281/TrendsinAgri.17139848

Abstract

CRISPR-based genome editing has shifted plant breeding from a century of pedigree and chance toward precise, hypothesis-driven modification of specific genes and regulatory elements. That shift accelerates trait delivery (disease resistance, quality, abiotic tolerance), opens pathways for de-novo domestication of wild relatives and enables targeted nutritional improvements. At the same time, real-world uptake is shaped by delivery challenges, pleiotropy, market and regulatory realities and public acceptance. This article synthesizes the current toolbox (nucleases, base editors, prime editors), delivery and transgene-free strategies, representative successes, regulatory trajectories across major jurisdictions and practical cautions and opportunities for breeders, companies and public-sector programs. The aim is pragmatic: show where CRISPR genuinely changes the breeding calculus, where it remains a complement to conventional methods and what steps teams should take to move edits from design to field responsibly.

Keywords: CRISPR, genome editing, plant breeding, base editing, prime editing, transgene-free, regulatory policy, de-novo domestication, gene drives (note: governance needed), trait stacks

Introduction

Plant breeding has always been an exercise in controlled change: choose parents, cross and then select offspring that carry the desired combination of alleles. CRISPR-based editing compresses parts of that process by enabling targeted nucleotide changes, promoter edits, or multi-gene knockouts directly in elite backgrounds. The practical consequence is not that breeding becomes trivial, but that breeders can aim at specific causal variants rather than depending on long introgression cycles or rare spontaneous mutations. This reduces the time and genetic drag associated with bringing a useful allele into an adapted line but it also raises scientific, regulatory and stewardship questions that must be managed deliberately.

The CRISPR toolbox

CRISPR is an umbrella for a set of molecular tools with different editing outcomes and trade-offs:

- **Nuclease-mediated knockouts (CRISPR–Cas9, Cas12a, etc.)**: create small insertions/deletions via non-homologous end-joining to disable genes (useful for removing susceptibility factors or repressors).
- **Base editors (cytosine or adenine deaminase fusions)**: convert single bases (C→T or A→G) without double-strand breaks, ideal for re-creating known single-base functional variants (for herbicide tolerance or enzyme changes).
- **Prime editing**: a guided "search-and-replace" capable of short insertions, deletions, or substitutions with less collateral damage still maturing for many crop species but increasingly reportable in the literature.
- **Cis-regulatory/promoter editing**: small edits to transcription factor or effector-binding sites that tune expression rather than eliminate function valuable when complete knockouts cause fitness costs.
- **Transient, DNA-free delivery (RNPs and viral vectors)**: reduce or eliminate foreign DNA in the final product and can simplify regulatory considerations in jurisdictions that distinguish between transgenic and transgene-free edits.

Delivery and transgene-free strategies the practical bottleneck

Editing success is a two-step problem:

(1) Getting the editing apparatus into target cells (transformation, particle bombardment, protoplast transfection, or viral/Agrobacterium-mediated delivery) and

(2) Recovering stable, fertile plants without unwanted baggage. Many crops are straightforward in this pipeline (rice, tomato, some legumes), while others (many cereals and most tree species) remain transformation-recalcitrant. Methods that deliver ribonucleoproteins (RNPs) or use transient expression minimize persistent foreign DNA and are increasingly favoured where regulatory regimes or market preferences differentiate between transgenic and transgene-free outcomes. Optimizing regeneration protocols, using morphogenic regulators to increase transformability and selecting elite genotypes amenable to editing are all practical levers breeders must budget for.

Representative successes and the early commercial landscape

A small but growing set of gene-edited plants has reached consumers or advanced field trials. Consumer-facing examples include the high-GABA tomato in Japan and gene-edited mustard greens introduced by commercial partnerships in the U.S.; industrial examples include waxy corn edits and trait lines used in processing or seed markets. Public-sector and private trials across cereals (wheat, rice, maize), oilseeds, tubers and horticulture show edited alleles for disease resistance (S-gene promoter edits, MLO knockouts), quality traits (starch composition, flavour) and abiotic tolerance. These case studies highlight two truths: edits that reproduce known, simple causal variants travel fastest; and market-oriented, consumer-obvious traits (taste, shelf life) can ease acceptance for first products.

Global regulatory snapshot (why the law matters to practice)

Regulation is the reality that determines whether an edited plant needs an onerous authorization pathway or can be released under simpler oversight.

- **United States:** A federal court vacated portions of the 2020 SECURE rule in December 2024, returning aspects of oversight to the pre-2020 framework while APHIS re-establishes its pre-2020 processes. The ruling created short-term uncertainty but APHIS has indicated that pre-existing confirmations and permits remain valid pending implementation details. This event has materially affected how developers plan translational timelines in the U.S. market.
- **European Union:** The Commission's 2023 proposal on "new genomic techniques" (NGTs) aims to create categories for plants that may be considered equivalent to conventionally bred varieties; the proposal and Parliament votes in 2024–2025 have moved negotiations forward but final rules and implementation remain in flux. This evolving framework will likely determine whether some edits escape the full GMO regime in the EU.
- **Japan, UK, Australia and others:** Several countries have adopted notification or clarified pathways for transgene-free edits (Japan, UK pathway changes) or are advancing field trials under defined frameworks (Australia trials, among others), demonstrating that regulatory diversity is large and project planning must be jurisdiction-specific.

Safety, off-targets and agronomic reality

Laboratory assays and high-fidelity nuclease variants have reduced off-target editing and in plants off-targets are often eliminated during line selection. But biological reality imposes two operational caveats:

(1) edits can have pleiotropic or background-dependent effects loss of an S-gene may increase resistance but reduce vigour under some environments; and

(2) complex traits (yield, drought resilience) are polygenic and do not yield to single edits. Thus CRISPR is often best used to *complement* quantitative breeding fixing specific liabilities, stacking effective variants, or recreating proven alleles in elite backgrounds rather than as a one-step solution for complex adaptation. Robust phenotyping across environments and detailed agronomic testing remain non-negotiable.

Social acceptance, labelling and market strategy

The social dimension is as consequential as the technical one. Consumer acceptance hinges on perceived benefits (taste, nutrition, sustainability), transparency and trusted actors. Early market successes that emphasize consumer benefits less bitterness, improved nutrition, or reduced waste are instructive: they demonstrate that clear, relatable consumer value combined with transparent communication can ease market entry. Labelling regimes or the absence of mandatory labelling affect trust and procurement decisions; breeders and firms should design communication and stewardship plans well before market launch.

Research frontiers shaping the next 5–10 years

A few technical currents will shape near-term prospects:

- **Improved prime editing and base editors** that work reliably across major crops will widen the menu of precise edits available.
- **De-novo domestication** editing a handful of domestication loci in wild relatives to create hardy but productive crops moves from proof-of-concept into field trials. This approach can rapidly create new crops better adapted to marginal environments. Better delivery systems (viral vectors, morphogenic regulators, improved regeneration protocols) will break transformation bottlenecks for recalcitrant species.
- **Integration with digital breeding and genomic selection**, where editing is one of several tools used by breeders to design and fix complex trait architectures.

Table: CRISPR edits, crops and status

S.no.	Crop	Trait / Goal	Target (typical)	Edit approach	Typical status
1	Tomato	Higher GABA (nutritional)	SlGAD (auto-inhibitory region)	Coding deletion / knockout	Commercial (Japan)
2	Mustard greens	Reduced bitterness / improved taste	Taste/bitterness loci (multiple)	Multiplex edits	Commercial rollout (limited)
3	Maize	Waxy starch (amylopectin)	Wx	Knockout (NHEJ)	Commercial / regulatory confirmations

4	Wheat	Powdery mildew resistance	TaMLO homoeologs	Knockouts (multiplex NHEJ)	Advanced field tests
5	Rice	Bacterial blight resistance	SWEET promoter EBEs	Promoter editing (multiplex)	Breeding lines / trials
6	Potato	Reduced bruising / processing quality	VInv / starch pathway genes	Knockout / allele edit	Product approvals / trials
7	Soybean	High oleic oil	FAD2 family	Knockout / base edit	Commercial development
8	Cassava	Virus resistance	eIF4E family	Knockouts	Greenhouse to field trials
9	Citrus	Canker resistance	CsLOB1 promoter	Promoter edit	Validation in controlled trials
10	Barley	Hull-less (naked) grain	NUD	Knockout	Proof-of-concept lines
11	Rice	Herbicide tolerance	ALS	Base editing (single AA change)	Research / trait intro
12	Tomato	Powdery mildew resistance	SlMLO1	Knockout	Mutants recovered
13	Rice	Aroma (fragrance)	BADH2	Knockout / base edit	Breeding lines
14	Cassava	Reduced cyanogenic glycosides	CYP79D	Targeted edits	Early trials
15	Maize	Increased yield components	Multiple regulators	Promoter or coding edits	Research / field trials
16	Banana	Non-browning / pathogen traits	PPO / susceptibility genes	Knockout / promoter edits	Research stage
17	Sorghum	Stay-green / drought traits	Senescence regulators	Regulatory tuning	Field evaluation
18	Tomato (wild → crop)	De-novo domestication (compact habit)	SP, SP5G, others	Multiplex edits	Proofs of concept
19	Cassava / Sweet potato	Improved nutrient profile	Vitamin / pathway genes	Targeted edits	Early research
20	Multiple	Reduced allergenicity (wheat, peanut)	Allergen genes (gliadins etc)	Multiplex knockouts	Experimental lines

Risks, governance and ethical points to manage

- **Gene flow and escapes:** As with any breeding innovation, the ecological context matters; containment, trait choice and escape mitigation must be assessed in field trials.

- **Equity and access:** If only large firms can afford editing pipelines, public-interest traits (nutrient enhancement, smallholder-relevant resistance) may lag unless public programs invest in capacity.
- **Intellectual property:** Seed access and freedom-to-operate can be complicated by patent thickets; public breeders should plan IP strategies and open CRISPR tool access where possible.
- **Transparency and consent:** Clear labelling or consumer engagement strategies, depending on jurisdictional requirements, will reduce distrust and support informed choice.

Conclusion

CRISPR and related editing technologies are not a panacea, but they are a transformative set of instruments that change what plant breeders can attempt and how quickly they can move from genotype to product. The technology's most immediate promise lies in recreating known beneficial alleles in elite backgrounds, tuning gene expression to reduce trade-offs and accelerating domestication or improvement of underused species. Realizing that promise requires high-quality genetics (clear causal variants), robust delivery and regeneration pipelines, careful multi-environment phenotyping, regulatory foresight and transparent engagement with supply-chain and consumer stakeholders. Where those elements come together, genome editing offers realistic, practical routes to crop improvements that matter for productivity, nutrition and resilience. Where they don't, editing remains a promising research tool that must be integrated thoughtfully into broader breeding and policy programs.

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