ISSN: 2634 - 8845

Journal of Earth and Environmental Science Research

SCIENTIFIC Research and Community

Research Article

Open Access

From Genome to Global Markets: Genetically Modified Sugarcane for Climate Resilience, Pest Control and the Circular Bioeconomy—A Review

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ABSTRACT

Genetically modified (GM) sugarcane promises more resilient cultivation and new industrial applications, yet technical breakthroughs do not automatically translate into sustainable commercialization. This qualitative literature review interprets peer-reviewed research published mainly during 2020-2026 alongside distinct official regulatory records to evaluate polyploid genomics, insect and virus resistance, drought tolerance, biomass and sucrose traits, biosafety, and value-chain adoption. Thematic synthesis shows that chromosome-resolved genomics and multiallelic editing have expanded the technical feasibility of targeted improvement. Selected field studies document promising drought and canopy-architecture effects, while BT sugarcane provides an important application for analyzing pest-control gains and resistance evolution. However, results remain event-, genotype- and environment-dependent; regulatory approval does not establish widespread planting or economic superiority. A comparison of Brazil, Pakistan and Indonesia demonstrates the need to distinguish event authorization from field replication, industrial recovery and market access. The article proposes a six-gate framework linking genetic validity, trait expression, field performance, biosafety, industrial fit and inclusive commercialization. It recommends matched comparators, independent multi-location trials, long-term stewardship, transparent event-specific regulatory records and integrated sugar-bioenergy economic assessments. GM sugarcane is best understood as a selective technological option whose sustainability depends on validated benefits and accountable governance rather than universal productivity promises.

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Received: October 16, 2026; **Accepted:** October 22, 2026; **Published:** October 30, 2026

Keywords: Genetically Modified Sugarcane, Saccharum Spp, Transgenic Crops, Genome Editing, Crispr/Cas, Bacillus Thuringiensis, Drought Tolerance, Biosafety Governance, Sugar-Bioethanol Value Chain, Circular Bioeconomy

Jel Classification Codes : O33, Q16, Q18, Q55, F13.

Introduction

Sugarcane at the food-fuel-climate intersection Sugarcane is simultaneously a food crop, industrial feedstock, energy resource and foundation of regional livelihoods. Its stalks supply crystalline sugar and ethanol, while bagasse, filter cake, molasses and field residues create additional pathways for electricity, fuels, soil amendments and biobased materials. This multifunctionality makes productivity improvements valuable but also complicates the definition of technological success. A higher cane yield may not mean higher recoverable sugar; more fiber may help a biorefinery while affecting milling conditions; and biological stress tolerance may have little economic value where the stress rarely occurs. Contemporary assessments increasingly connect sugarcane genomics to integrated biorefining and the circular economy rather than to field productivity alone Climate uncertainty intensifies this multidimensional challenge. Water deficits, high temperatures, changing pest pressures and variable harvesting windows can reduce both the amount and quality of cane delivered to mills. Sugarcane is particularly consequential because establishment, ratooning and processing require coordinated decisions across several seasons and many actors. Investment in a novel variety therefore affects farm input requirements, mill throughput, contractual arrangements and the utilization of residues. A credible appraisal of genetically modified sugarcane must trace outcomes through this interconnected system, instead of reducing the debate to a binary judgment about the acceptability of genetic engineering. A cross-crop synthesis of climate and land-use effects on pest distributions further shows why local insect pressure, host plants and shifting seasonal risk must be monitored instead of treated as static background conditions [1-5].

The Biological Constraints on Improvement

Modern sugarcane cultivars originate from crosses involving Saccharum officinarum and S. spontaneum and contain unusually complex, high-ploidy genomes. Multiple chromosome copies, aneuploid variation and partially differentiated parental contributions challenge conventional mapping and targeted manipulation. The chromosome-scale reconstruction of the cultivar R570 substantially improved the representation of this architecture, while related assemblies have clarified the genomic composition and evolution of cultivated hybrids. These advances do not eliminate complexity; they make previously inaccessible allelic structure more tractable, particularly for resistance loci and regulatory networks Conventional breeding remains indispensable. Genetic recombination, field selection and recurrent evaluation

have created the cultivars that underpin commercial supply, and genomic selection is improving the efficiency of these processes. However, long evaluation cycles and environmental variation can slow responses to emerging threats. Genomic prediction, improved phenotyping and identification of non-additive genetic effects provide complementary tools rather than an obsolete alternative to biotechnology. A sensible comparison asks what a transgene or edit can achieve beyond the feasible performance of well-bred conventional material under matched conditions [6-12].

The Research Gap

Public-facing explanations of genetically modified sugarcane frequently combine established applications, plausible research aims and untested benefits in the same promotional narrative. Insect resistance, reduced drought loss, increased sucrose, faster maturation and greater biomass convertibility may all be desirable, but their evidential maturity differs sharply. The existence of a molecular target cannot establish a stable phenotype; a controlled field result cannot establish a nationwide productivity gain; and an approval decision cannot establish commercial uptake. This review treats those distinctions as fundamental analytical questions rather than minor qualifications A further gap lies between scientific literature on individual traits and policy discussions about trade, seed systems and industrial processing. Studies of resistance biology seldom report mill-level returns, while market acceptance studies typically concern GM food in general rather than sugar made from a specific event. Consequently, stakeholders may make investment decisions using evidence generated at incompatible scales. The present review integrates genomic capability, agronomic performance, biosafety, downstream product requirements and socioeconomic inclusion into a single framework and applies it to Brazil, Pakistan and Indonesia as contrasting settings [13-18].

Questions, Objectives and Contribution

The review addresses seven linked questions: what polyploid genomics has enabled; which traits possess field-level evidence; what ecological and biosafety constraints matter; how three national pathways differ; where industrial and trade effects arise; what determines socially legitimate adoption; and how policy should sequence research and deployment. Its purpose is not to estimate a pooled treatment effect. Instead, it compares the meanings, evidential strength and transferability of reported findings across biological, institutional and value-chain contexts. This approach is appropriate when heterogeneous evidence includes experiments, conceptual studies, reviews and regulatory documents with different units of analysis The proposed contribution is an integrated six-gate model linking genetic validity, trait expression, field performance, biosafety, industrial performance and market inclusion. Passing one gate does not imply passing the next. The model encourages scientific humility without dismissing valuable innovation and supports investment decisions that can be revised when new evidence emerges. Figure 1 introduces this framework, which structures the literature synthesis and subsequent policy discussion. Rather than predicting a universally superior GMO variety, the review identifies the conditions under which a specific genetic intervention could produce a durable, measurable and equitable advantage [19-21].

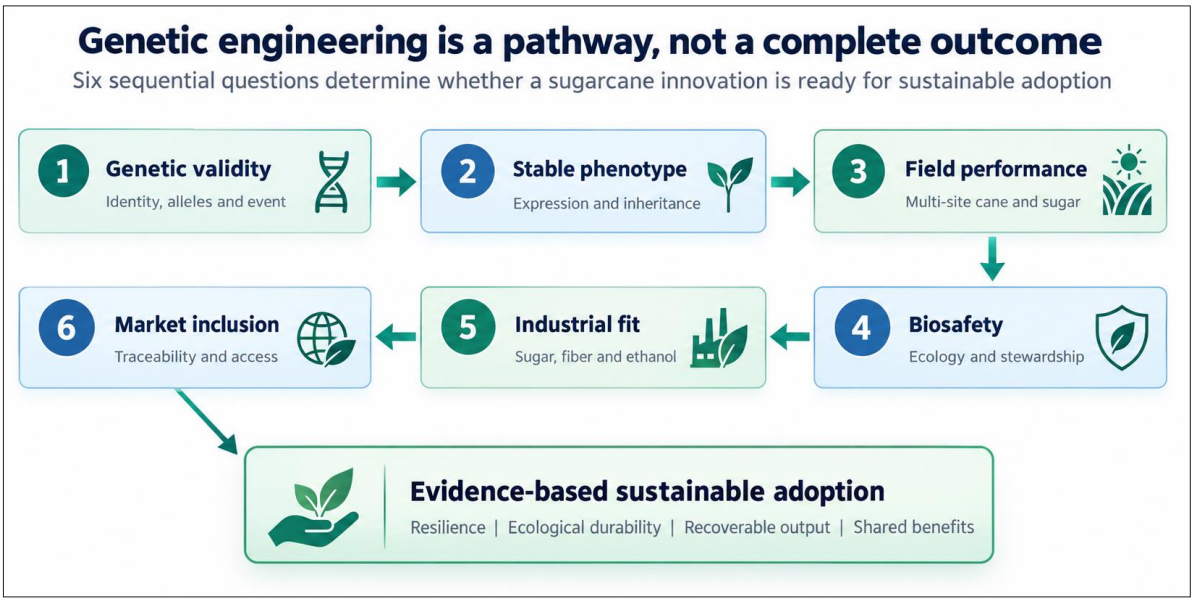


Figure 1: Integrated Six-Gate Framework from Genetic Intervention to Sustainable Adoption.

Source: Author Synthesis of the Cited Literature.

Figure 1 should be read from left to right: an event may pass molecular assessment without yet demonstrating field superiority, and field superiority can remain commercially inaccessible without processing fit and market acceptance. The final outcome is deliberately conditional, not automatic. Each stage therefore requires its own evidence and decision criteria; positive results upstream should not be treated as substitute evidence for downstream feasibility.

Literature Review: Concepts, Technology and Theory

Genomic Architecture, Genetic Diversity and Breeding Pathways

Sugarcane's genomic heterogeneity makes gene dosage central to both experimental design and interpretation. An edit affecting only some homologues can generate a quantitative response rather than a simple loss-of-function phenotype. Copy number, homoeologous variation and chromosomal rearrangements can also influence molecular assays and the stability of traits propagated

by stem cuttings. Genome assemblies and chromosome-specific methods provide a basis for designing allele-aware markers, interpreting inherited variation and detecting unintended changes. Yet validation must remain cultivar-specific because a reference assembly cannot represent every elite genetic background Breeding strategies extend from genomic prediction and marker-assisted selection to transgene insertion, RNA interference and targeted editing. They operate on different causal assumptions: selection exploits standing variation, transgenesis may introduce an additional protein or regulatory function, RNA interference can downregulate transcripts, and editing can alter endogenous sequences. These approaches often interact in an applied program, because an engineered event must ultimately be incorporated into competitive germplasm and evaluated against established cultivar benchmarks. International proposals for genomics-guided improvement therefore emphasize collaboration, shared datasets and field phenotyping as much as sequence generation Genomic prediction offers a useful counterfactual for claims that precision biotechnology is the only way to accelerate gains. Disease resistance and ratooning ability have been examined using prediction models, including algorithms that attempt to capture complex or non-additive inheritance. The general lesson is that gain depends on reliable training populations, target environments and appropriate phenotypes. Computational sophistication does not substitute for representative field data, particularly when performance changes between plant-cane and ratoon crops. A genetically modified variety should therefore be compared not only with an unmodified near-isogenic control but also with the best realistically available breeding alternatives [22-28].

Transgenesis, Rna Interference and Genome Editing

Transgenic development commonly involves constructing a genetic cassette, introducing it into competent tissue, regenerating plants and characterizing independent events. In sugarcane, tissue culture response, transformation efficiency, transgene expression and soma clonal effects can vary with genotype. Simple educational diagrams of one gene entering one cell convey the principle but understate event characterization, segregation constraints and clonally propagated multiplication. Precise claims require verification of the inserted sequence, genomic location or copy number when relevant, as well as the trait's stability in subsequent vegetative generations Genome editing changes the practical question from whether a new sequence can be introduced to which native allele combinations can be altered reproducibly. CRISPR-based targeting of an acetolactate-synthase-related herbicide-tolerance system and investigations of liguleless1 illustrate different strategies, from editing biochemical susceptibility to tailoring canopy architecture. The multiallelic nature of sugarcane makes target design and molecular assessment much more demanding than in a simple diploid crop. Prospective applications of editing in related grasses must also be interpreted cautiously because transformation performance and developmental effects may not transfer directly between new methods of haploid induction, increasingly resolved assemblies and improved editing systems may eventually make it easier to disentangle allele functions. Nonetheless, prospects of transgene-free editing require a distinct regulatory analysis from transgenic plants carrying foreign DNA. Mechanisms used to remove delivery constructs, demonstrate absence of unwanted transgenic material and characterize intended changes remain technically and institutionally important. An edit described as precise at the molecular target cannot be assumed to have zero off-target or pleiotropic consequences throughout a complex life cycle [29-36].

Trait-to-Performance Pathways

The meaning of insect resistance is relatively direct at the molecular level when a plant expresses a Bt protein that affects a susceptible target pest. Agronomic benefit, however, depends on pest occurrence, the level and timing of expression, pest population genetics, stalk injury, harvest losses and resistance management. Disease resistance has additional layers because pathogens may evolve and viral pressure varies spatially. Conversely, drought tolerance is inherently multicomponent: water status, root function, growth maintenance and recovery may change independently of sucrose accumulation or ratooning. These differences argue against presenting all GM traits on a single undifferentiated effectiveness scale Cell-wall modification, biomass yield and sucrose concentration represent a different functional cluster. Reduced lignin may improve saccharification for second-generation ethanol, but industrial processing depends on pretreatment chemistry, sugar losses, enzyme use and logistics. Altered leaf angle may improve light interception and biomass under defined planting conditions without necessarily shortening the crop cycle. A change in Brix alone is not a sufficient metric of recoverable sugar per hectare, which also depends on stalk biomass, sucrose purity and milling recovery. Figure 2 separates the main trait categories by measured endpoint and remaining evidence requirement [37-40].

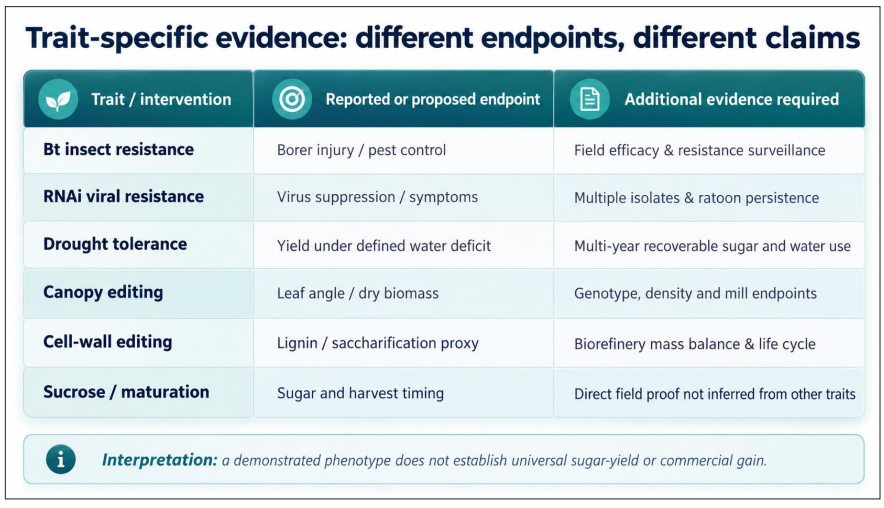


Figure 2: Trait-Specific Endpoints and Evidence Gaps.

Source: Author Synthesis; Illustrative Categories are not a Quantitative Ranking.

Figure 2 shows why a trait cannot be described simply as "higher productivity". Pest resistance, lignin reduction, water-stress response and harvest timing must be evaluated using different measurement protocols, comparators and industrial endpoints. The matrix is a research-design aid and not a pooled comparative estimate of the relative merits of the interventions.

Biosafety, Environmental Governance and Diffusion

Biosafety is broader than acute toxicity. Ecological assessment considers non-target species, resistance evolution, changes in pest-control regimes, potential movement of genetic material, persistence of volunteer plants, and the characteristics of production ecosystems. For vegetatively propagated sugarcane, the frequency of seed-based gene flow can differ from seed-propagated crops, but a sweeping assertion that gene flow or ecological exposure is impossible would exceed available evidence. Site- and event-specific appraisal should accompany a transparent plan for monitoring and reporting adverse outcomes Institutional approaches differ markedly across countries and distinguish genetically modified events from some forms of targeted genome editing. Regulatory reform can reduce uncertainty while raising questions about transparency, consumer choice and the evidence used to grant exemptions. Debate over precision-breeding legislation illustrates that scientific characterization and social legitimacy are related but not identical. Technical compliance may coexist with skepticism where public information is limited or decision-making excludes affected stakeholders Adoption theories help explain why technically promising technologies do not automatically diffuse. Growers assess expected yields, costs, availability of planting material and freedom to market harvested products; mills assess volume, quality and operational disruption; regulators examine safety and accountability; and buyers consider traceability and reputation. General public-acceptance research reports that attitudes toward GM technologies depend partly on perceptions of risk, benefit and information credibility. Evidence from other commodities or regions therefore offers a framework for inquiry, not a numerical forecast of sugarcane uptake [41-46].

The Sugarcane Circular Bioeconomy

The bioeconomy provides the strongest reason to broaden the evaluation from cane yield to usable industrial output. A conventional sugar mill and ethanol distillery can be understood as a linked material and energy system in which sucrose, molasses, bagasse, vinasse and electricity have different costs and market values. Biotechnology aimed at one fraction can affect allocation among others. Consequently, economic evaluation should compare total system value under transparent boundary conditions: the type of refinery, available infrastructure, electricity prices, enzyme use, byproduct demand and the treatment of emissions A process-level sustainability assessment of bagasse-derived ethanol in Colombia demonstrates that alternative pretreatments and feedstock logistics alter conversion outcomes and environmental-economic performance; it does not directly establish the impact of any specific GM sugarcane event Trade adds a further layer. Exporters may face event-specific import rules, identity-preservation costs and contractual requests for non-GM cane-derived products. Those requirements can arise even when the chemistry of refined sugar is not a reliable indicator of its crop origin. Therefore, market access should be assessed using destination-specific law, buyer requirements and practical segregation, not broad claims that GM sugar is always prohibited or always accepted. A sustainable development calculation must include both on-farm advantages and the possible opportunity cost of exclusion from particular channels [47].

Method: Interpretive Qualitative Literature Review

Review Design and Epistemic Position

This study employs a qualitative literature review organized around problem-driven thematic interpretation. It is neither a systematic literature review nor a meta-analysis, and it does not claim exhaustive retrieval, protocol registration or PRISMA compliance. The object of analysis is the relationship between technologically demonstrated traits and the conditions required for their sustainable use. A narrative-integrative design is suitable because the available evidence spans genome assembly, molecular experiments, field trials, breeding analyses, ecological studies, consumer research, regulatory announcements and industrial-system reviews, each addressing different questions at different scales.

Identification and Critical Selection of Literature

The main academic window is 2020 to October 2026. Journal literature was identified using concept combinations covering sugarcane, Saccharum, genome editing, transgenic, BT, RNAi, drought, sucrose, biomass, bioethanol, governance and consumer acceptance. Preference was given to peer-reviewed research and reviews with explicit methods and identifiable journal DOI records, while broader governance studies were retained where sugarcane-specific evidence was thin. Official national records were examined separately to establish the chronology and scope of approvals; they are not counted as journal articles. Selection was purposive and relevance-driven rather than represented as an exhaustive database census. Searches were iteratively refined when a key theme was poorly represented; backward examination of reference lists supported contextual coverage. The review does not report an exhaustive database search or numeric screening flow, and this limits reproducibility relative to a formal systematic review.

Data Interpretation and Thematic Coding

A qualitative evidence matrix was built conceptually around intervention, biological mechanism, experimental setting, measured outcome, comparator, external validity, environmental uncertainty and commercial implications. Records were interpreted within seven overlapping themes: enabling genomics; insect and disease resistance; abiotic stress; sugar and biomass processing; national regulatory trajectories; ecological durability; and market or inclusion conditions. The synthesis privileges distinctions between observations, mechanistic explanations, prospective hypotheses and policy inferences. Where outcomes cannot be compared quantitatively, the review records their different contexts rather than averaging them into a pooled estimate.

Appraisal and Inference Discipline

The review distinguishes five broad evidence levels: laboratory molecular confirmation; greenhouse or controlled-condition phenotype; limited site-specific field performance; independent or multi-location field replication; and monitored commercial outcomes. This is a heuristic for interpretive appraisal, not a validated numerical quality scale. Evidence of a particular benefit is also separable from evidence of biosafety or regulatory approval. Reported percentages are reproduced only when they are tied to named experimental designs, control groups and environmental conditions. Unreported acreage, yield impacts, cost reductions and market premiums are not inferred from approval notices or promotional statements.

Reflexivity, Uncertainty and Limitations

A central limitation is uneven documentation across technologies

and regions. Some sugarcane-specific results come from small field studies, while broader institutional conclusions come from research on multiple crops or from public regulatory statements rather than peer-reviewed sugarcane market evaluations. The paper explicitly avoids treating these heterogeneous sources as interchangeable. A second limitation is temporal: as of October 2026, regulatory and adoption conditions remain subject to change. Finally, the qualitative approach supports theory-building, comparison and evidence-based recommendations but cannot establish global causal effects or provide a universal cost-benefit ratio without harmonized longitudinal datasets.

Results: Thematic Synthesis of Evidence

Polyploid Genomics Has Shifted Feasibility, Not Eliminated Constraints

The first theme is a genuine improvement in the technical feasibility of modern sugarcane biotechnology. High-quality genome assemblies, allele-aware descriptions and genomic selection models have substantially strengthened the ability to nominate targets and characterize complex pedigrees. They also expose why simple Mendelian assumptions remain inadequate: target dosage may vary, transcriptional responses can be buffered by homologues, and cultivar backgrounds may alter the expression of an ostensibly identical intervention. Technological capability should therefore be described as expanding the range of testable hypotheses rather than guaranteeing predictable agronomic results Genome-enabled breeding is also producing a more realistic account of environmental interactions. Field phenotyping and selection for ratooning, disease resistance and biomass yield demonstrate the continuing importance of measurements over several crop cycles. Breeding reviews emphasize the practical tension between high-throughput genomic data and laborious evaluations of stem yield and quality. This suggests a productive division of labor: molecular methods can identify candidates, while breeding networks and trial systems determine whether the candidates improve actual production portfolios. An event that works in one elite cultivar may still fail to outperform an existing alternative in another region.

BT Sugarcane Provides a Concrete but Conditional Insect-Resistance Case

Brazil supplies a visible commercialization pathway for insect-resistant GM sugarcane. The Brazilian biosafety authority approved the commercial use of CTC20Bt in June 2017, targeting injury associated with the sugarcane borer Diatraea saccharalis Subsequent research has investigated Bt proteins and the evolutionary vulnerability of pest populations, including evidence of experimentally selected resistance to Cry1Ab and Cry1Ac. The combined lesson is neither that Bt cane cannot work nor that it offers permanent protection: efficacy depends on specific pest populations, toxin exposure and resistance-management conditions Additional work on transgenic sugarcane expressing Cry1Ac against the giant borer Telchin licus illustrates that susceptibility and exposure differ across pest species. The biologically effective intervention has to match the target insect's feeding biology and the tissue in which the relevant protein is expressed. The importance of species-specific testing is reinforced by findings on epicuticular wax differences associated with the initial attack of D. saccharalis; plant resistance is influenced by factors beyond a single insecticidal protein. Future comparisons should measure stalk damage, harvest losses, insecticide use, non-target exposure and yield at the same sites Resistance evolution is a primary durability concern. A 2025 study of Brazilian D. saccharalis populations reported resistance inheritance and an absence of detectable fitness penalties in the strains examined, highlighting the risk of assuming that susceptible populations will naturally displace resistant ones when exposure is reduced. The evidence calls for regionally realistic resistance-management strategies, refuge assessment, surveillance of susceptibility and integration with other pest-control measures. Refuge requirements and operational strategies should be designed from event-specific regulatory and ecological evidence rather than transferred mechanically from maize or cotton A global synthesis of monitoring records through the first 25 years of BT crop deployment documented both cases of practical resistance and persistent susceptibility, demonstrating why exposure, refuges and local pest genetics must be assessed together Evidence from BT cotton also indicates that appropriately designed non-BT refuges can counter resistance even when simple recessive-resistance assumptions do not hold, although these findings cannot be transferred to sugarcane without crop-specific validation [48-52].

Viral Resistance Illustrates the Role of Rna-Based Technologies Plant viruses create a distinct challenge because control often depends on clean planting material, vector management and varietal resistance. Experimental sugarcane research has investigated RNA interference to suppress viral targets, including genes associated with sugarcane mosaic virus. Such work demonstrates the feasibility of designing sequence-specific resistance pathways, but laboratory or greenhouse resistance is not equivalent to sustained suppression across diverse viral isolates and environments. The stability of silencing across ratoon generations and the risk of viral escape require particular attention in a vegetatively propagated crop A practical advantage of the RNA-based approach is its flexibility in selecting targets; a corresponding limitation is dependence on sequence conservation, expression context and pathogen diversity. Field evaluation should incorporate virus diagnostics, symptom scoring, crop growth, planting-material health and yield outcomes under representative infection pressure. RNAi crops and RNAi-based biopesticides also raise different exposure and acceptance issues, yet research on the social license of RNAi technologies underscores the need to communicate mechanisms clearly rather than assuming that their perceived novelty guarantees favorable reception [53,54].

Drought Performance Is Encouraging but Stress- And Genotype-Dependent

The drought literature demonstrates why experimental detail matters. Sugarcane transcriptomic and metabolomic studies identify pathways related to osmotic regulation, oxidative stress, photosynthetic maintenance and water-use efficiency, providing candidate mechanisms for intervention. Yet different genotypes respond differently to stress intensity, timing and recovery conditions. A physiological marker associated with tolerance is not automatically a predictor of harvested sucrose. The relationship between maintaining green leaf area and maximizing industrial output can change across growth stages and water regimes A particularly informative experimental example is the field evaluation of sugarcane expressing TaDREB2B under a drought-responsive promoter. Under limited irrigation, the reported transgenic line displayed better physiological responses and approximately 41.9% higher cane yield than the comparator in the studied trial setting, with attention also given to quality traits and ratooning. This is meaningful evidence of a field phenotype, not a forecast of the same percentage improvement under all climates or cultivars. Repeated independent tests, alternate stress profiles, industrial recovery metrics and economic evaluation are needed before the outcome can be generalized to an entire production zone The drought-tolerance pathway also raises a resource-allocation

question. Where irrigation water is limited, stable performance under scarcity may create value by reducing production variance even when maximum yield under favorable conditions does not increase. Conversely, an apparently tolerant event might increase area planted in water-stressed regions and undermine basin-level savings. Evaluation should therefore include water productivity, soil health, crop cycle, ratoon persistence and collective water governance. The sustainability of a molecular improvement cannot be inferred from plant-level measurements without understanding the landscape in which water is allocated [55-58].

Sugar Concentration, Early Maturity and Biomass Are Different Objectives

The available literature supports progress in genetic and genomic understanding of sucrose accumulation, fiber content and yield-related components, but it does not justify treating all improved traits as simultaneously realized in existing commercial GMO cane. Association studies and genomic prediction for sucrose and fiber provide candidate targets and selection strategies; they do not demonstrate that a transgenic construct will reliably increase both characteristics. Because early maturation is an agronomic and scheduling trait, any claim that GM sugarcane can always be harvested earlier requires direct field evidence measuring physiological maturity and commercially optimal recovery, not merely faster seedling growth Canopy architecture offers a specific mechanistic success: multiallelic editing of the LIGULELESS1 locus generated altered leaf inclination in sugarcane, and one tested line showed an 18% increase in dry biomass yield in a replicated field experiment. The result is important because it demonstrates a link from targeted editing through plant form to a field endpoint. Nevertheless, the measured endpoint was dry biomass, not universally increased crystal sugar or an automatically shortened harvest cycle. Economic benefit would depend on planting density, stalk composition and the industrial use to which the additional biomass is directed Another illustrative result comes from CRISPR-directed modification of the SoLIM transcription factor, which lowered lignin content in edited sugarcane lines under the reported experimental conditions. Lower recalcitrance could aid lignocellulosic conversion, but moving from cell-wall chemistry to viable ethanol production requires mass-balance, pretreatment, enzyme-efficiency and life-cycle analyses. The optimal event for a second-generation bioethanol refinery might differ from the optimal variety for refined sugar or power generation. This reinforces the need for end-use-specific breeding objectives and for considering tradeoffs among desirable properties

Table 1 distinguishes experimentally measured traits from value-chain claims. It also identifies the next type of evidence required before a result can be interpreted as a general improvement in recoverable sugar, mill performance or economic value.

Table 1: Selected Trait-level Evidence and Boundaries of Inference. Source: Author Synthesis of Cited Experimental Studies.

Intervention and source	Reported study endpoint	Interpretation and verification need
TaDREB2B transgenic line (Xiao et al., 2022)	Approximately 41.9% higher cane yield for the reported line under limited-irrigation field conditions	Site- and stress-specific effect; independent multi-location trials, recoverable sugar, ratooning and economics are needed.
LIGULELESS1 editing (Brant et al., 2024)	Altered leaf inclination; 18% more dry biomass for one tested line in replicated field conditions	Dry biomass is not a direct measure of refined sugar; confirm genotype, density, cane quality and mill recovery.
SoLIM editing (Laksana et al., 2024)	Reduced lignin content in edited sugarcane	Cell-wall phenotype does not establish ethanol profitability; test pretreatment, conversion, mass balance and life-cycle impacts.

Taken together, these experiments establish different levels of technological promise rather than a common yield statistic. Their findings should be interpreted relative to each study's comparator, environment and actual measured endpoint, not combined into a universal GMO productivity estimate.

Comparative National Trajectories Reveal Different Institutional Gates

Brazil represents the earliest of the three selected regulatory pathways to commercial BT cane. The 2017 authorization was a concrete legal milestone, not a substitute for quantified independent adoption statistics. More recent studies on resistance mechanisms and pest management identify a continuing need for stewardship as deployment develops. Assessing the Brazilian experience therefore requires time-series evidence for planting area, pest control, environmental monitoring, cane yield, mill performance and product-market requirements. The strongest analytical lesson is that commercialization creates new monitoring obligations rather than ending the scientific evaluation process Pakistan offers a more recent regulatory milestone. An October 2025 government announcement reported biosafety approval of two sugarcane lines, CABB-IRS and CABB-HTS, and indicated that national uniform yield testing would follow the approval is a significant reported institutional development but should not be interpreted as evidence of nationwide performance or large-scale adoption in 2026. Likewise, a public announcement that vegetative propagation removes gene-flow risks should be treated as a regulator's stated position, not as proof that all conceivable ecological pathways are absent. The comparison turns on the distance between authorization, cultivar registration, seed cane multiplication and grower use Indonesia has a longer and different documentary sequence. Indonesia's food-regulatory authority reported circulation approvals concerning GM sugarcane events NXI-4T and NXI-6T in 2012, while an agricultural ministry decision addressed feed safety for NXI-4T in 2018 These documents establish event-specific regulatory actions; they do not establish commercial hectares, superior performance or industry-wide sugar self-sufficiency. Claims about drought tolerance or productivity advantage require event-linked field studies and transparent comparisons under Indonesian agroecological conditions. Indonesia is thus a useful case of the gap between regulatory history and publicly demonstrated diffusion at scale Figure 3 visually distinguishes the reported regulatory milestones without implying that any country has achieved a comparable level of field adoption [58].



Figure 3: Regulatory Milestones Reported for Indonesia, Brazil and Pakistan.

Source: Official Institutional records; Dates Refer to Distinct Approval Types.

The separate timeline rows indicate that the listed authorizations are not necessarily approvals for the same product use. Their dates cannot be compared as if each proved an equal level of commercial adoption. Distinct legal decisions also differ in their geographic scope and product categories, so a shared calendar does not provide a common denominator for diffusion.

Figure 3 therefore places the three trajectories on separate rows and marks their information gaps explicitly. This prevents the misleading inference that a calendar date, without a common deployment denominator, establishes greater success.

Table 2 compares the evidentiary meaning of the three national milestones. It deliberately excludes unverified planting-area estimates, since the records concern different legal acts and do not constitute matched measures of adoption [59-61].

Table 2: The Scope and Limitations of Selected National Regulatory Milestones. Source: Author Synthesis of cited official Records

Country and dated milestone	What the record establishes	What it does not establish
Indonesia—2012 food-event records; 2018 feed-safety decision	Event-specific food/feed administrative determinations involving NXI-4T and NXI-6T	National commercial acreage, repeated agronomic advantage or increased recoverable sugar.
Brazil—2017 CTC20Bt authorisation	Authorisation for commercial use of an insect-resistant sugarcane event	A comparable region-wide effect size or indefinite protection against evolving borers.
Pakistan—2025 CABB-IRS / CABB-HTS announcement	Reported biosafety milestone and intended downstream national testing	Completed nationwide yield tests, grower-level diffusion or mill-level economic returns.

The cases illustrate contrasting stages of regulatory and commercial readiness rather than a ranking of national biotechnology success. Future benchmarking should compare the same event-linked indicators—trial replication, grower adoption, crop performance and market access—across all three settings. The country comparison is most informative when it is framed as a difference in evidence and institutional sequencing rather than a league table. Brazil has an early public commercial approval, Pakistan has a newly reported national biosafety step, and Indonesia has older specific food/feed regulatory records. None of these facts alone produces a comparable statistic for hectares planted or a defensible ranking of realised productivity.

Ecological and Market Risks are Cumulative Rather Than Isolated

Environmental performance cannot be judged only by whether a GM crop is safe in a single regulatory test. Repeated selection pressure can change pest susceptibility; changed insecticide use can alter non-target exposure; large-area planting can affect genetic diversity; and different crop-residue strategies can change soil carbon and nutrient flows. A rigorous appraisal links event-specific risk assessment to landscape monitoring and integrated pest management, while keeping causal claims proportional to observed data. This approach is compatible with the goal of reducing agrochemical dependence but avoids describing such reductions as automatic for every engineered event Evidence across multiple crop systems indicates that climatic warming and land management can modify pest phenology, population expansion and biological control, reinforcing the need to stratify surveillance by place and season public acceptance is also differentiated by product, geography and use. Acceptance of a non-food industrial feedstock cannot be presumed identical to acceptance of sugar for food consumption, animal feed, or bioethanol. Studies of consumer reactions and regional attitudes

show that perceived benefits, baseline beliefs, information source and trust affect reported preferences. Because these studies are not representative surveys of all sugarcane customers, their findings are used here to identify mechanisms of acceptance rather than to assign a universal willingness-to-pay estimate or rejection rate

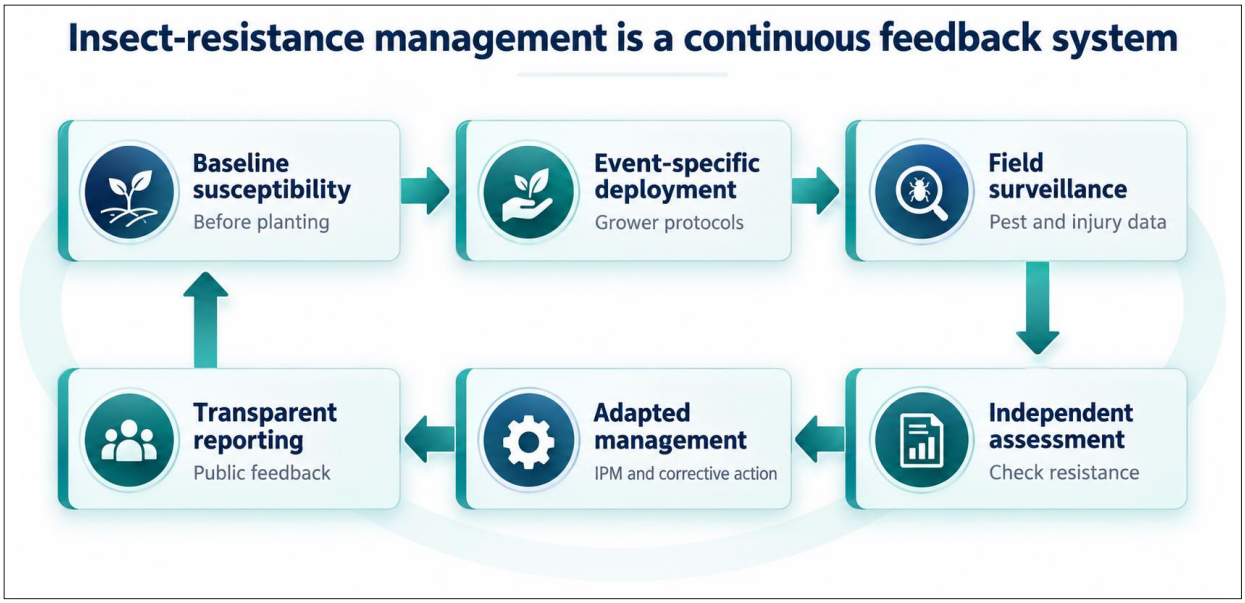


Figure 4: Conceptual Surveillance and Adaptation Cycle for BT Sugarcane.

Source: Author Synthesis of Pest-resistance Studies the arrows in

Figure 4 signify continuous learning: surveillance may reveal a need to update management, increase scrutiny, or revisit how and where an event is deployed. In particular, the pathway returns independent resistance assessments to growers and regulators, making corrective action a continuing obligation rather than a one-time registration condition. connects the ecological and institutional strands through a resistance-management cycle. It indicates that deployment of insect-resistant cane should begin with baseline pest susceptibility and field surveillance and should feed observations back into agronomic and regulatory action. The diagram is deliberately conceptual: the precise location, scale and design of refuges, thresholds and other interventions require event-specific evidence and local regulatory guidance. Treating monitoring as part of commercialisation is particularly important where a resistant population may incur little measurable fitness cost

Discussion and Analysis

Answering The Central Question: Innovation Must Cross Six Gates

The synthesis points to a decisive conceptual distinction: technical feasibility is not adoption readiness. The first gate requires confirmed target sequence and event identity; the second a reproducible phenotype; the third an effect on relevant field endpoints; the fourth an acceptable and monitored environmental profile; the fifth a fit with the processing system; and the sixth accessible, legally marketable and socially legitimate implementation. Failures are not necessarily evidence that genetic engineering itself is ineffective. They may reflect an unsuitable comparator, inconsistent pest pressure, an uneconomic processing configuration or market exclusion. Conversely, apparent benefits should not be attributed to the transgene when background genetics or management differ between test plots

This six-gate approach answers RQ1 and RQ2 by locating genomic breakthroughs and field outcomes on a shared but non-equivalent continuum. Recent genome assemblies and editing studies clearly improve the possibility of specific interventions, while drought and canopy studies show that some engineered phenotypes have moved beyond laboratory proof of concept. Yet large commercial claims must be evaluated with independent, multi-year benchmarks. Future reports should specify event identity, comparator genetics, agronomic setting, replicate structure, cane and sugar yields, variability and information about the crop cycle. These reporting elements would materially improve the transferability of findings

Trait-Specific Investment Portfolios Are Preferable to Universal Promises

Different constraints warrant different technological portfolios. Where severe borer pressure is reliably documented, insect-resistant germplasm and integrated pest management may offer a clearer route to value than editing primarily for altered maturity. In chronically water-stressed zones, the stability of cane and recoverable sugar across drought years is more informative than yield under well-watered trial plots. A mill linked to second-generation ethanol may prioritize lignocellulosic characteristics and biomass throughput. These are distinct investment theses with different outcome measures and counterfactuals; combining them under one generic GMO productivity claim makes both science and capital allocation weaker A portfolio approach also permits non-GM alternatives where they outperform or carry less uncertainty. Genomic selection, improved clean-seed systems, irrigation management, crop protection and precision phenotyping can generate substantial benefits without introducing a particular engineered event. The appropriate comparison is marginal benefit per unit of cost, risk and institutional effort, not biotechnology versus an artificially static conventional baseline. Integrating advanced breeding with targeted engineering, rather than presenting them as rivals, creates more robust options for farmers and breeders facing heterogeneous soils and climates

Translating Regulatory Approval into Verifiable Industry Performance

The cases of Brazil, Pakistan and Indonesia answer RQ4 by demonstrating that national regulatory records measure different stages. Biosafety approval indicates that a competent body reached a decision within a particular legal remit. Variety release, multiplication, planting, harvest, processing and market realization require further conditions that may be governed by other institutions. Comparing countries should therefore use matched milestones and verified implementation indicators rather than inferring commercial success from a single regulatory notice. The distinction is particularly important for newer approvals whose downstream outcomes are not yet publicly documented For Brazil, a priority is independently reported longitudinal evidence on planted area, injury reduction, management costs and resistance evolution across different production regions. For Pakistan, the immediate research need is open access to national trial methods, results and regulatory follow-up for each line. For Indonesia, it is essential to connect event-specific approvals with replicated performance data and the chain of decisions affecting estate and smallholder deployment. These priorities are different but share a common logic: stronger information governance would enable a more rigorous cost-benefit assessment and reduce polarized debate

Resistance Evolution Requires Stewardship a as A Design Feature

The lesson from BT resistance research is that ecological durability must be built into deployment before large-scale expansion. Monitoring should measure shifts in pest sensitivity and damage patterns, while governance should specify corrective actions and roles for technology providers, producers, public laboratories and extension services. In settings where resistance may arise without large fitness costs, post-approval monitoring cannot be assumed to be temporary. The costs of refuge design, surveillance and integrated management belong in the economic model, not in unrelated environmental appendix Cross-crop evidence links sustained control to monitoring programs and appropriate refuge strategies rather than the indefinite efficacy of any single insecticidal protein A comparable logic applies to viral resistance, though biological mechanisms and management options differ. Target-sequence evolution, mixed infections and the distribution of infected cuttings can undermine a seemingly promising result. Such risks can be mitigated through diagnostics, multiplication standards, breeding diversity and responsive surveillance rather than reliance on a single protective gene or RNA sequence. Regulatory dossiers and research papers would benefit from explaining how event performance will be tracked through successive ratoon crops and how adverse observations will be communicated to growers.

A Value-Chain Approach Changes the Economic Definition of Benefit

The economic value of a GM trait can be represented conceptually as the incremental value of recoverable sugar, ethanol, electricity and other coproducts, less additional costs of seed cane multiplication, cultivation, monitoring, licensing, processing adjustment, traceability and trade compliance. This formulation is not an estimated equation; it clarifies where measurements are required. For instance, improved cane survival under drought might raise mill utilization, whereas lower lignin might reduce processing intensity for a specialized biofuel plant but offer limited benefit at a mill without suitable conversion facilities An integrated Colombian study of ethanol production from sugarcane bagasse illustrates why environmental impacts, economic feasibility and process conditions should be assessed jointly when extrapolating from biomass chemistry to refinery performance Distribution matters as much as aggregate value. A proprietary event may generate positive returns for a vertically integrated plantation while creating barriers to smallholder adoption if planting material is costly or licensed on restrictive terms. Conversely, increased and more stable output may benefit growers if cane-price formulas fairly reflect improved recoverable sugar and if extension services can support correct stewardship. Transparent contracts, accessible diagnostics, benefit-sharing and capacity-building should therefore be included in the adoption pathway. Social legitimacy is not an ornamental final stage; it influences compliance, long-term performance and the credibility of market claims [62].

Trade, Labeling and End-Use Differentiation

Claims about international rejection of products from GM cane should be specified by destination and commodity. A shipment of cane-derived sugar, molasses, bioethanol or industrial intermediate may face different documentation or contractual requirements. Regulators can distinguish the status of a cultivated event from labeling, import authorization and food or feed evaluation. Private buyers may also impose conditions beyond statutory minima. Because these parameters change over time, export-readiness review should document the relevant jurisdiction, event, product category and contractual chain rather than relying on a static global map of GMO acceptance The governance implication is to plan traceability proportionally and early. Segregation of planting material, identity preservation and chain-of-custody records may be necessary for some channels, but they carry costs that vary by infrastructure and the scale of mixed production. Investment scenarios should compare separate GM and non-GM supply routes where economically relevant and evaluate potential market opportunities as well as risks. Research into consumer perception further suggests that providing simple, reliable information about purpose and oversight is more defensible than either exaggerated safety assurances or promotional claims of universal consumer enthusiasm

A Phased and Adaptive Implementation Roadmap

Figure 5 translates the foregoing synthesis into an implementation roadmap. The first phase establishes a trait-specific problem and credible comparator. The second confirms molecular identity and phenotype; the third conducts representative multi-location and multi-year trials with industrial quality measures. The fourth completes applicable biosafety and registration requirements and establishes stewardship and market arrangements. The fifth permits carefully monitored deployment linked to decision points for scale-up, suspension or redesign. These stages create an evidence-to-investment sequence rather than a prediction that all events will qualify for commercialization.

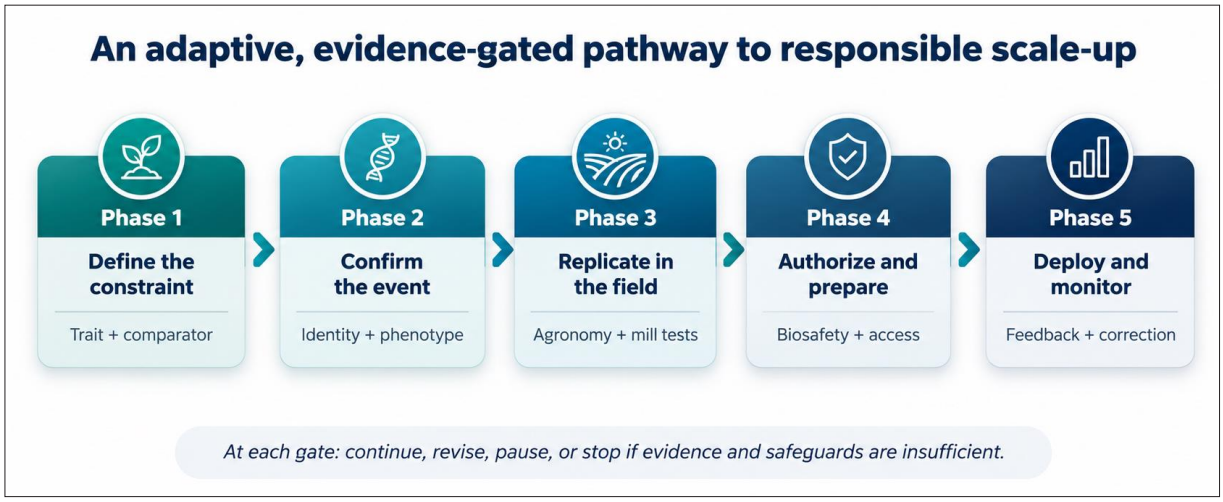


Figure 5: Phased Implementation Roadmap with Reversible Evidence Gates.

Source: Author Synthesis of the Review

Figure 5 emphasizes reversible investment gates. Strong outcomes at one stage justify further investigation, while weak evidence, unacceptable risks or missing market access justify revising or stopping a proposed scale-up. A proposed event may therefore return to a previous experimental phase when comparative evidence or safeguards remain inadequate. A practical roadmap also needs measurable governance indicators. Candidate metrics include the share of trials with independently documented comparators, variability in recoverable sugar across drought years, insect susceptibility trends, observed non-target effects, smallholder access to healthy planting material, traceability costs and documented buyer acceptance. Public agencies could publish a summary of the decision status of each event without compromising proprietary sequences or personal information. Universities and extension organizations could conduct independent replication, while mills provide transparent aggregate data on processing performance. Such arrangements would make both successful and unsuccessful innovation easier to learn from.

An Agenda for Further Interdisciplinary Research

Six research priorities arise. First, compare engineered lines with elite conventional alternatives across representative climate-risk gradients. Second, combine molecular characterization with repeated ratoon and industrial-quality outcomes. Third, investigate ecological durability with robust baseline and post-deployment monitoring. Fourth, quantify processing tradeoffs among sugar recovery, biomass utilization and second-generation ethanol. Fifth, evaluate event-specific market acceptance and traceability, not generic attitudes toward genetically modified foods. Sixth, assess distributive effects for smallholders, labor and technology providers under realistic legal and contracting arrangements

The most useful empirical designs would be interdisciplinary and geographically explicit. Agronomists can describe pest pressure and water regimes; molecular scientists can characterize target integrity and expression; engineers can measure recoverable product streams; economists can calculate incremental returns and risk distributions; and social researchers can investigate trust and informed participation. Data standards should distinguish units such as cane tonnes, dry biomass, recoverable sucrose, liters of ethanol and greenhouse-gas intensities. Without those distinctions, results from otherwise rigorous research risk being aggregated into misleading claims of generalized superiority.

Policy Implications for Indonesia and Comparable Producers

For Indonesia, the evidence supports a problem-oriented rather than technology-led strategy. National priorities could begin by mapping region-specific drought, pest and ratooning losses, identifying whether modern conventional cultivars already address them, and defining where an engineered event might create incremental value. The regulatory histories of NXI-4T and NXI-6T deserve a transparent synthesis of what was approved, what field evidence was used and whether commercial performance has been independently documented. This does not prejudge the technology's value; it enables prospective investments to be matched with real constraints and verifiable benefits For the wider sugarcane sector, a staged strategy should connect public research, breeding companies, plantations, independent growers, sugar mills, bioethanol investors and environmental agencies. Cooperative field networks can lower the cost of multi-location trials, while standardized industrial tests can prevent misplaced emphasis on field tonnage alone. Regulators should retain the capacity for case-by-case assessment and transparent revision as evidence changes. The ultimate measure of success is not the number of events authorized but the net improvement in resilient, environmentally responsible and economically accessible output that can be substantiated across the value chain.

Conclusion and Future Directions

GM sugarcane has advanced from an aspirational concept to a field of diverse, increasingly specific technological options. Improved reference genomes and allele-aware editing have made difficult molecular targets more tractable, while selected field studies demonstrate that engineered traits can alter pest susceptibility, drought performance and biomass-related characteristics. These are substantive achievements, yet they should not be translated into universal claims of higher sugar, faster harvest or permanent resistance. The measured endpoint, genetic background, environmental context and independent replication determine what a result can support the review's central finding is that commercial value depends on the alignment of six conditions: genetic integrity, stable trait expression, agronomic performance, ecological and biosafety acceptability, processing-system benefit and inclusive market access. The three country examples illustrate different sequences of regulatory and technological development, but none permits regulatory timing alone to serve as proof of superior productivity. A valid comparison requires event-linked

evidence from the laboratory through field deployment and industrial processing, together with transparent documentation of uncertainties. A holistic recommendation is to prioritize the trait and production problem before choosing the technological platform, then require independent, multi-location testing with explicit benchmarks for both cane and recoverable products. Resistance management, water stewardship, planting-material systems, monitoring responsibilities and market traceability should be incorporated in the design stage, not attached after commercialization. Public agencies can support this process through accessible summaries of event status, interoperable data standards and independent evaluation facilities, while investors can adopt phase-gated decisions that are revised when evidence fails to justify further expansion Future research should strengthen long-term ecological monitoring, study genotype-by-environment interactions over successive ratoons, quantify conversion efficiencies for specialized biorefineries and analyze who receives the economic gains. It should also investigate how policy instruments, technology licensing and procurement requirements affect farmer access and export options. These questions connect genetic innovation with the social and industrial systems necessary to realize it. The most defensible future of GM sugarcane is therefore neither unconditional endorsement nor blanket rejection, but selective, evidence-calibrated deployment under credible stewardship.

References

1. Ahmad K, Ming R (2024) Harnessing Genetic Tools for Sustainable Bioenergy: A Review of Sugarcane Biotechnology in Biofuel Production. Agriculture 14: 1312.
2. Mehdi F (2024) Factors affecting the production of sugarcane yield and sucrose accumulation: suggested potential biological solutions. Frontiers in Plant Science.
3. Dias HB (2021) High-yielding sugarcane in tropical Brazil – Integrating field experimentation and modelling approach for assessing variety performances. Field Crops Research.
4. Wang D (2025) Unlocking the potential of sugarcane: Advances in genomic innovation, biorefinery technologies, and stress resilience, and circular bioeconomy. Industrial Crops and Products.
5. Ma CS (2025) Crop pest responses to global changes in climate and land management. Nature Reviews Earth & Environment 6: 264–283.
6. Bao Y (2024) A chromosomal-scale genome assembly of modern cultivated hybrid sugarcane provides insights into origination and evolution. Nature Communications.
7. Zhang J (2025) The highly allo-autopolyploid modern sugarcane genome and very recent all polyploidization in Saccharum. Nature Genetics.
8. Cursi DE (2022) History and Current Status of Sugarcane Breeding, Germplasm Development and Molecular Genetics in Brazil. Sugar Tech.
9. Yadav S (2020) Accelerating Genetic Gain in Sugarcane Breeding Using Genomic Selection. Agronomy 10: 585.
10. Yadav S (2021) Improved genomic prediction of clonal performance in sugarcane by exploiting non-additive genetic effects. Theoretical and Applied Genetics.
11. Sandhu KS (2022) Integrated Approach in Genomic Selection to Accelerate Genetic Gain in Sugarcane. Plants 11: 2139.
12. Brant EJ, (2024) The extent of multiallelic, co-editing of LIGULELESS1 in highly polyploid sugarcane tunes leaf inclination angle and enables selection of the ideotype for biomass yield. Plant Biotechnology Journal.
13. Xiao S (2022) Field evaluation of TaDREB2B-ectopic expression sugarcane (Saccharum spp. hybrid) for drought tolerance. Frontiers in Plant Science.
14. Tuncel A (2023) Genome-edited foods. Nature Reviews Bioengineering.
15. Stanton J, Rezai G, Baglione S (2021) The effect of persuasive/possessing information regarding GMOs on consumer attitudes. Future Foods.
16. Luo T, Liu X, Lakshmanan P (2023) A Combined Genomics and Phenomics Approach is Needed to Boost Breeding in Sugarcane. Plant Phenomics.
17. Wang H (2025) Sugarcane genetics: Underlying theory and practical application. The Crop Journal.
18. Srithawong S (2026) Sugarcane Breeding in the Genomic Era: Integrative Strategies and Emerging Technologies. Plants 15: 286.
19. Piperidis N, D'Hont A (2020) Sugarcane genome architecture decrypted with chromosome-specific oligo probes. The Plant Journal.
20. Healey AL (2024) The complex polyploid genome architecture of sugarcane. Nature.
21. Mahadevaiah C (2021) Genomic Selection in Sugarcane: Current Status and Future Prospects. Frontiers in Plant Science.
22. Zhang X (2025) International research initiative on genomics-guided sugarcane breeding. Molecular Plant.
23. Gao SJ, Wang QN (2025) Sugarcane Breeding: Physiology, Genomics, and Phenomics for Agronomic Traits Development. Tropical Plant Biology.
24. Islam MS (2021) Experimental evaluation of genomic selection prediction for rust resistance in sugarcane. The Plant Genome.
25. Islam MS, et al. (2023) A first look at the ability to use genomic prediction for improving the ratooning ability of sugarcane. Frontiers in Plant Science.
26. Chen C, (2023) Genomic prediction with machine learning in sugarcane, a complex highly polyploid clonally propagated crop with substantial non-additive variation for key traits. The Plant Genome.
27. Mohan C, Easterling M, Yau YY (2021) Gene Editing Technologies for Sugarcane Improvement: Opportunities and Limitations. Sugar Tech.
28. Hussin SH (2022) An Updated Overview on Insights into Sugarcane Genome Editing via CRISPR/Cas9 for Sustainable Production. Sustainability 14: 12285.
29. Brant E, Zuniga-Soto E, Altpeter F (2025) RNAi and genome editing of sugarcane: Progress and prospects. The Plant Journal.
30. Oz MT (2021) CRISPR/Cas9-Mediated Multi-Allelic Gene Targeting in Sugarcane Confers Herbicide Tolerance. Frontiers in Genome Editing.
31. Li C, Iqbal MA (2024) Leveraging the sugarcane CRISPR/Cas9 technique for genetic improvement of non-cultivated grasses. Frontiers in Plant Science.
32. Guo Y (2024) In vivo induction of sugarcane (Saccharum spp.) haploids by genome editing. Plant Physiology.
33. Huguet-Tapia JC (2025) Ensuring effective removal of transgenes before release of genome-edited crops. Nature Biotechnology.
34. Krishna SS (2023) Transgene-Free Genome Editing for Biotic and Abiotic Stress Resistance in Sugarcane: Prospects and Challenges. Agronomy 13: 1000.
35. Sakuno CIR (2024) Transgenic sugarcane expressing Bacillus thuringiensis Cry1Ac protein offers new possibilities for controlling the giant borer, Telchin licus (Drury), a pest

difficult to control. Crop Protection.
36. Widyaningrum S (2021) Induction of resistance to sugarcane mosaic virus by RNA interference targeting coat protein gene silencing in transgenic sugarcane. Molecular Biology Reports.
37. Laksana C, Sophiphun O, Chanprame S (2024) Lignin reduction in sugarcane by performing CRISPR/Cas9 site-direct mutation of SoLIM transcription factor. Plant Science.
38. Xiong H (2023) A Genome-Wide Association Study and Genomic Prediction for Fiber and Sucrose Contents in a Mapping Population of LCP 85-384 Sugarcane. Plants 12: 1041.
39. Jenkins D (2023) Regulation of plants developed through new breeding techniques must ensure societal benefits. Nature Plants.
40. Husaini AM, Sohail M (2024) Agrochemical-free genetically modified and genome-edited crops: Towards achieving the United Nations sustainable development goals and a 'greener' green revolution. Journal of Biotechnology.
41. Caccamo M (2023) New precision-breeding law unlocks gene editing in England. Nature Biotechnology.
42. Vanderschuren H (2023) A new chance for genome editing in Europe. Nature Biotechnology.
43. Gbadegesin LA (2022) GMOs in Africa: Status, adoption and public acceptance. Food Control.
44. Jin S (2022) Consumer responses to genetically modified food in China: The influence of existing general attitudes, affect and perceptions of risks and benefits. Food Quality and Preference.
45. Medani KR (2024) Societal perceptions and attitudes towards genetically modified (GM) crops, feed, and food products in the Middle East, North Africa, and Turkey (MENAT) region: A systematic literature review. Food Quality and Preference.
46. Wang JD (2025) Current status and research progress of sugarcane stem borers management. European Journal of Agronomy.
47. Rodrigues JG (2025) Inheritance and fitness costs of Cry1Ab and Cry1Ac resistance in Brazilian populations of Diatraea saccharalis (Lepidoptera: Crambidae). Crop Protection.
48. Cheng X (2024) Trends in the global commercialization of genetically modified crops in 2023. Journal of Integrative Agriculture.
49. Cooper EA (2024) A sweet victory for sugarcane genomics. Nature Plants.
50. Wartha CA (2022) Classification of sugarcane genotypes susceptible and resistant to the initial attack of sugarcane borer Diatraea saccharalis using epicuticular wax composition. Phytochemistry.
51. Tabashnik BE, Fabrick JA, Carrière Y (2023) Global patterns of insect resistance to transgenic Bt crops: The first 25 years. Journal of Economic Entomology 116: 297–309.
52. Guan F (2023) Refuges of conventional host plants counter dominant resistance of cotton bollworm to transgenic BT cotton. iScience 26: 106768.
53. Hidayati WN (2021) Distinguishing resistances of transgenic sugarcane generated from RNA interference and pathogen-derived resistance approaches to combating sugarcane mosaic virus. Indonesian Journal of Biotechnology.
54. Tardin-Coelho R (2025) A systematic review on public perceptions of RNAi-based biopesticides: Developing Social Licence to Operate. npj Sustainable Agriculture.
55. Contiliani DF (2023) Drought-triggered leaf transcriptional responses disclose key molecular pathways underlying leaf water use efficiency in sugarcane (Saccharum spp.). Frontiers in Plant Science.
56. Li H (2023) Comparative transcriptomic analyses of two sugarcane Saccharum L. cultivars differing in drought tolerance. Frontiers in Plant Science.
57. Yang S (2023) Global Responses of Autopolyploid Sugarcane Badila (Saccharum officinarum L.) to Drought Stress Based on Comparative Transcriptome and Metabolome Profiling. International Journal of Molecular Sciences 24: 3856.
58. Government of Pakistan, Press Information Department (2025) NBC approves GM sugarcane and cotton varieties for commercialization. 23 October.
59. Badan Pengawas Obat dan Makanan (BPOM) (2013) Notification of food-circulation decisions concerning GM sugarcane events NXI-4T and NXI-6T (2012 decisions).
60. Ministry of Agriculture, Republic of Indonesia (2018) Decision No. 214.2/Kpts/H/08/2018 on feed safety of GM sugarcane event NXI-4T.
61. Centro de Tecnologia Canavieira (CTC) (2017) CTC20Bt commercial authorization announcement. 8 June.
62. Piedrahita-Rodríguez S, Ortiz-Sánchez M, Higuita Vásquez JC, Cardona Alzate CA (2025) Ethanol from bagasse obtained during non-centrifuged sugar production: A comprehensive sustainability analysis in the Colombian context. Waste and Biomass Valorization 16: 1397–1410.

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