

Genome Editing and Precision Breeding Strategies for Sustainable Soybean Improvement

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ABSTRACT

The drawbacks of input-heavy agricultural growth - such as stagnant yields, environmental degradation and climate vulnerability - have made it necessary to reorient global agricultural strategy toward productivity gains that are also environmentally sustainable. This shift, widely termed the Second Green Revolution, emphasizes sustainable intensification: higher and more stable yields with a smaller environmental footprint, more efficient resource use, and greater resilience to biotic and abiotic stress. Genome editing, particularly CRISPR-Cas-based precision breeding, is examined here as the primary technological driver of this transition in the Indian context, because it enables targeted, often transgene-free trait improvement under a comparatively streamlined regulatory pathway (SDN-1/SDN-2). The three-decade global experience with genetically modified (GM) crops is discussed only as comparative background - both as an evidence base on the agronomic, economic and environmental performance of transgenic technologies, and as a policy lesson on the regulatory and public-acceptance challenges that genome editing must navigate differently. This paper positions India's recent genome-editing milestones (genome-edited rice, the approval of DMH-11 mustard, and progress in soybean genome editing) alongside a critical, evidence-based comparison of conventional breeding, transgenic (GM) crops and genome editing, with soybean developed as the central case study given its strategic importance to India's edible-oil security. It argues that genome editing, integrated with sound agronomic practice, rigorous biosafety assessment and transparent, policy-aligned governance, offers a scientifically grounded and practically feasible route to sustainable agricultural transformation in India.

Keywords: CRISPR/Cas systems, Second Green Revolution, Genome editing, Soybean, Precision breeding, Climate-resilient crops, Food security, Regulatory framework

INTRODUCTION

The Green Revolution and the Emergence of the Second Green Revolution

The Second Green Revolution is a paradigm shift from yield-centric agricultural intensification to a sustainability-centric, knowledge- and technology-driven food system, which simultaneously enhances productivity, nutritional security, climate resilience and environmental integrity. While the first Green Revolution was predominantly about maximizing cereal yields, the

second Green Revolution is about sustainable intensification – producing more food from the same or fewer inputs while minimizing ecological damage and increasing resilience to climate variability (Godfray et al., 2010; Pingali, 2012; Rockström et al., 2017). This standard addresses emerging challenges of stagnating yields, land and water scarcity, climate change, biodiversity loss and malnutrition especially in smallholder-dominated agrarian economies from both Indian and global perspectives (World Bank, 2008; FAO, 2017; Pingali et al., 2019). The second Green Revolution

is therefore not a single technology-driven event but a systemic transition involving biological, digital and institutional innovations to ensure long-term food and livelihood security.

Second Green Revolution Concept

Here, the Second Green Revolution is conceptualized as a model shift from input-intensive yield maximization to sustainable, resilient and nutrition sensitive agricultural systems. The second Green Revolution, unlike the first one, is based on sustainable intensification: more and better food from existing land and water resources, without environmental externalities and increased climate resilience (Godfray et al., 2010; Rockström et al., 2017; FAO, 2017). This transition attempts to address current issues such as climate change, resource scarcity, loss of biodiversity and persistent malnutrition from Indian and international perspectives through the use of high-end biological inventions, digital technologies and improved institutional arrangements rather than depending on chemical inputs (World Bank, 2008; Pingali et al., 2019).

How to Reach the Second Green Revolution

The second Green Revolution is built on the convergence of sophisticated crop improvement technologies, climate

smart agronomic practices and supportive socio-economic and policy frameworks. The scientific community has repeatedly stressed the importance of integrating genomics-assisted breeding, biotechnology-based transgenic technologies, especially genome editing based on CRISPR-Cas9 and precision agriculture to develop crops with higher yield potential, improved stress tolerance and better nutrient-use efficiency under changing climatic conditions (Godfray et al., 2010; Tester & Langridge, 2010; Qaim, 2020). It is also important to adopt climate-smart agriculture, which combines improvement of productivity with adaptation and mitigation measures such as efficient water use, reduced greenhouse gas emissions and resilience to abiotic stresses (FAO, 2021; Rockström et al., 2017). In the Indian and global context, strengthening agricultural research systems, improving extension services, use of online resources for decision making and inclusive access to technologies for small and marginal farmers (World Bank, 2008; Pingali et al., 2019; FAO, 2017) are also important in achieving this transformation.

Table 1 enlisting the principal agricultural technologies that the scientific literature associates with the Second Green Revolution, alongside their current status of maturity in Indian agricultural research and deployment.

Table 1. Technological Pillars of the Second Green Revolution

Technology	Domain	Representative function	Maturity in Indian soybean/crop research
Conventional breeding	Genetics	Recombination and selection within sexually compatible gene pools	Mature; foundation of current cultivar development
Marker-assisted breeding	Genetics/Genomics	Selection using DNA markers linked to traits of interest	Mature; routinely used in public-sector programmes
Genomic selection	Genomics	Selection on genome-wide predicted breeding values	Emerging; pilot use in a few Indian crop programmes
Speed breeding	Breeding logistics	Extended photoperiod/controlled environments to compress generations	Emerging; limited infrastructure in soybean
Genome editing (CRISPR-Cas and related)	Precision biotechnology	Targeted, often transgene-free modification of characterized genes	Early-stage; experimental in Indian soybean, regulatory pathway defined (SDN-1/2)
Transgenic biotechnology	Biotechnology	Introduction of genes from unrelated species	Mature technically; restricted regulatory deployment beyond Bt cotton and DMH-11
AI-assisted breeding	Digital/Computational	Machine-learning-guided parent selection, trait prediction and gRNA design	Nascent; largely at research-pilot stage in India
Precision agriculture	Agronomy/Digital	Site-specific input management using sensors and geospatial data	Growing adoption among larger/progressive farms

Remote sensing	Digital	Satellite/aerial monitoring of crop condition and stress	Operational at research and some extension levels
UAV (drone) phenotyping	Digital	High-throughput field-level trait measurement	Emerging; expanding in public research stations
High-throughput phenotyping	Phenomics	Rapid, often automated measurement of plant traits at scale	Limited infrastructure; concentrated in a few ICAR/university centers
Digital agriculture / decision support	Digital	Data-driven advisories for input timing and management	Expanding through public and private extension platforms
Multi-omics integration	Systems biology	Combined genomic, transcriptomic, proteomic and metabolomic analysis	Research-stage; growing in genomics-capable institutes
Soil microbiome engineering	Biological	Manipulation of rhizosphere microbial communities for plant benefit	Early research stage in India
Biofertilizers	Biological	Microbial inoculants improving nutrient availability/uptake	Established and commercially available, uneven farmer adoption
Biological control	Crop protection	Use of natural enemies/microbials to manage pests and pathogens	Established for some pests; underused relative to chemical control

Changes necessary for the second green revolution

Realizing the second Green Revolution requires fundamental changes in cropping systems, resource management, innovation pathways and governance structures. Major changes include a move away from mono-cropped cereal systems to nutrient-dense crops, the use of input-efficient and stress-tolerant varieties, and the broad application of precision nutrient and water management to combat declining soil health and groundwater depletion (Tilman et al., 2002; Pingali, 2012; FAO, 2017). Technological change has to be accompanied by institutional reforms such as policies that incentivize environmentally friendly practices, rationalize subsidies for fertilizer and promote public-private partnerships for technology dissemination (World Bank, 2008; Pingali et al., 2019). Innovative biotechnological tools such as genetically modified and genome-edited crops are seen as critical components of this transformation, enabling targeted improvement of traits and reduced chemical use, given science-based regulatory systems and public sector involvement, especially in developing countries such as India (Qaim & Zilberman, 2003; Klümper & Qaim, 2014; FAO, 2022).

1. GM CROPS AS COMPARATIVE CONTEXT: CONCEPT, GLOBAL ADOPTION AND LESSONS FOR GENOME EDITING

Conceptual framework of Genetically engineered crops

Genetically modified (GM) crops are plants genetically altered using recombinant DNA technology to introduce a trait that does not occur naturally in the species, most commonly insect resistance, herbicide tolerance, disease resistance, abiotic-stress tolerance or nutritional enhancement. Unlike conventional breeding, which recombines existing variation within sexually compatible gene pools, transgenic technology allows well-characterised genes - including those from unrelated species - to be introduced directly. GM crops have now been cultivated commercially for nearly three decades, generating a large empirical record of their agronomic, economic and environmental performance. This section synthesizes that global evidence base, not to make a case for GM crops themselves, but to extract comparative lessons - on efficacy, adoption patterns, regulatory pathways, and public acceptance - with direct relevance to how genome-edited crops are likely to be developed, regulated, and received in India.

Global GM Crop Adoption:

Current Situation and Trends Global adoption has increased steadily since the first commercial release of GM crops in 1996, reflecting continued farmer

acceptance and economic viability. The International Service for the Acquisition of Agri-biotech Applications (ISAAA) reported that in 2022–2023, more than 30 countries on six continents grew GM crops on some 200 million hectares. From 1996-2023, global GM crop area planted has surpassed 3.0 billion hectares making agricultural biotech the fastest adopted crop technology in the world (ISAAA Brief 58, 2023).

While a handful of countries dominate the GM crop scene globally, the patterns of adoption vary considerably between the developed and developing economies. The United States continues to be the largest producer of GM crops with an estimated 74 million hectares, followed by Brazil (~66 million hectares), Argentina (~28 million hectares) and Canada (~13 million hectares). India is among the top five GM growing countries in the world with an estimated area of 11.5–12 million hectares sown to GM crops (ISAAA, 2023; ISAAA Infographics, 2024), but only one GM crop, Bt cotton, has been commercially approved.

A characteristic feature of global GM crop adoption is the large share in developing countries. ISAAA estimates that 90-95% of the 17-18 million farmers growing GM crops worldwide are smallholder and resource-poor farmers, mostly in Asia, Africa and Latin America. The pattern suggests that GM technology is a scale-neutral innovation that can benefit a wide variety of farm sizes and production systems.

Distribution of Crops and Traits Around the World:

The use of genetically modified crops is restricted to a small number of crops. This is a reflection of both the demand in the market and the appropriateness of those species for the deployment of traits in a biological setting. The most widely cultivated genetically modified crop is soybean, which accounts for almost half of the total area of GM crop production around the world. Soybean is followed by maize, cotton, and canola. A total of over 95% of the world's genetically modified crop plantings are accounted for by these four crops (ISAAA, 2023).

Regarding traits, herbicide tolerance (HT), insect resistance (IR), and stacks of both traits in stacked varieties constitute the bulk of the global GM crop portfolio. By herbicide tolerance (HT), insect resistance (IR) and combinations of both traits in stacked varieties. Stacked traits have shown the fastest growth in recent times particularly in maize and cotton, which mirrors the need to address multiple constraints simultaneously under intensified production systems. The increasing occurrence of stacked traits also signifies a shift from

problem-by-problem solutions to systems-level resilience, a trait that is well aligned with the aspirations of the Second Green Revolution.

Agronomic Performance and Yield Outcomes

One of the most debated aspects of GM crops concerns their impact on yield. It is now well established that GM technologies primarily function by protecting attainable yield rather than increasing genetic yield potential per se. A meta-analysis of over 140 studies in different crops and regions found that GM crops yielded, on average, 22 percent higher than their non-GM equivalents, with far larger increases in developing countries (Klümper and Qaim, 2014).

Most of these yield gains are a result of reduced yield losses to insects, weeds, and diseases, rather than intrinsic gains in photosynthetic efficiency or biomass production. This distinction is particularly important in stress-prone agro-ecosystems where yield variability poses a greater risk to farmer livelihoods than absolute yield ceilings. In such cases GM crops add to the stability of production, a key requirement of sustainable intensification.

Recent Advances in Crop Biotechnology in India

India's recent advances in crop biotechnology have proceeded on two parallel but related tracks: transgenic technology and, more recently, genome editing. The best example of the former is Dhara Mustard Hybrid-11 (DMH-11), a transgenic hybrid of *Brassica juncea* developed at the Center for Genetic Manipulation of Crop Plants (CGMCP), University of Delhi. The system is based on the barnase-barstar system as first described by Mariani et al. (1990) in which a ribonuclease gene from *Bacillus amyloliquefaciens* (barnase) induces male sterility and its inhibitor (barstar) restores fertility in the hybrid progeny. Jagannath et al. (2002) at CGMCP developed and field-validated the specific barnase/barstar line combinations, together with a bar selectable marker, that form the basis of DMH-11's hybrid seed production system in Indian mustard based on this mechanism. This combination enabled breeders to successfully exploit heterosis in a crop otherwise mostly self-pollinating—a long-standing limitation in mustard breeding. Confined field trials of ICAR indicated yield improvement of about 28% over the national check variety, Varuna (Press Information Bureau [PIB], 2026), broadly in line with the 20-30% heterotic advantage reported for previous hybrids under the same breeding program (Yadava et al., 2021). Much of India's edible oil is imported, and so there

is a compelling economic case for increasing the productivity of local mustard - and DMH-11 has become something of a proxy in the broader, still unresolved debate about genetically modified crops in the country.

Genetically Modified Crops: Promise and Peril

World-wide adoption of GM crops has grown rapidly since their commercial release in 1996. GM crops were grown in 2019 on 190.4 million hectares in 29 countries, with cumulative plantings over 25 years exceeding 2.7 billion hectares, the ISAAA said, adding that GM technology is one of the fastest adopted innovations in agricultural history.

But the global acceptance of GM crops has not stopped them being controversial in India. Public opposition and policy inertia have been fueled by concerns related to biosafety, corporate control of seeds, ecological risks and ethical considerations, especially regarding food crops. This has resulted in India's GM portfolio being restricted to Bt cotton, approved in 2002, with other GM crops encountering regulatory delays or moratoria despite strong scientific support.

The downside of this record is well documented and deserves comparable weight in any policy-relevant assessment. Documented concerns include the evolution of insect and weed resistance under sustained single-trait selection pressure (e.g., pink bollworm resistance to Bt cotton in parts of India, and glyphosate-resistant weeds in herbicide-tolerant cropping systems elsewhere), the concentration of proprietary seed technology among a small number of multinational providers, the recurring cost of trait licensing for resource-poor farmers, gene-flow and coexistence concerns with non-GM crops and wild relatives, and persistent public distrust rooted partly in the limited transparency of early regulatory decisions. In India specifically, it is these documented risks and social costs - rather than any single adverse biosafety finding - that have kept food-crop GM approvals, other than DMH-11 mustard, in regulatory abeyance since Bt cotton was approved in 2002. Any assessment of GM technology's relevance to the Second Green Revolution needs to weigh these risks and costs against its demonstrated agronomic and environmental benefits, rather than treating either side of the ledger in isolation.

India's Agricultural Imperatives

India's agricultural challenges are structurally different from those the first Green Revolution was designed to solve, and they are multi-dimensional in nature. Yield

growth in rice and wheat, the two staple cereals that anchored the first Green Revolution, has plateaued, while pulses and oilseeds continue to be produced at productivity levels well below the world average. Biotic stresses - pests, diseases and weeds - account for an estimated 20–30% of annual crop losses (ICAR, 2021), and roughly 52% of India's cultivated area is rainfed and therefore acutely vulnerable to climate variability. These production constraints are compounded by rising input costs and stagnating or falling farm returns for smallholders, who make up the overwhelming majority of India's farming population. Conventional breeding is a necessary and useful tool to address these constraints, but is inherently slow and constrained by the genetic diversity available within sexually compatible gene pools. Targeted biotechnological approaches – such as transgenic (GM) technologies, and increasingly genome editing – can introduce specific traits more rapidly and precisely, a capability that is particularly relevant as the pace of climate change accelerates.

2. GENOME-EDITED RICE OF INDIA AND EMERGING POLICY MILESTONES

More recently, DRR Rice 100 (Kamla) and Pusa DST Rice 1 illustrate a shift to precision breeding through genome editing rather than through transgenesis. Both varieties were developed by the Indian Council of Agricultural Research (ICAR) using CRISPR-Cas based SDN-1 and SDN-2 editing, a technique that modifies the plant's own genome without the insertion of foreign DNA (ICAR, 2025). DRR Rice 100 is derived from Samba Mahsuri (BPT 5204) background at ICAR-Indian Institute of Rice Research, Hyderabad. It is edited for higher grain number per panicle and matures in about 130 days, which is about 20 days earlier than its parent. It has a stronger culm, which helps in lodging resistance without compromising on the grain quality of Samba Mahsuri for which it is known (ICAR, 2025). The shorter growth period also has knock-on effects on demand for irrigation and fertilizers, and for methane emissions. Instead, ICAR-IARI developed Pusa DST Rice 1 from MTU 1010, which was edited for tolerance to saline and alkaline soils. ICAR reports yield gains of 9.66-30.4% over the parent line (ICAR, 2025) under these stress conditions. Overall, ICAR projects that wider cultivation of the two varieties could raise productivity, cut greenhouse-gas emissions and save an estimated 7,500 million cubic meters of irrigation water nationally, alongside improved resilience to drought and salinity

(ICAR, 2025) - though it is worth noting these are the developing institution's own projections rather than figures independently verified through third-party field trials, and some of ICAR's performance claims for the varieties have already drawn public challenge from independent scientists (Telegraph India, 2025). Together, DMH-11 and the two genome-edited rice varieties represent a fairly natural progression in Indian crop biotechnology: from the introduction of new genetic material for hybrid seed production, to the more precise editing of existing genes within elite breeding lines. Both approaches hint at something bigger than yield alone - resource efficiency, climate resilience, environmental sustainability - and the global evidence on GM crop adoption only partially supports this. Klümper and Qaim (2014) conducted a meta-analysis and found that GM adoption has typically led to lower pesticide use and higher yields across the globe, but the size of these effects differ significantly by crop, trait, and local farming system and should not be seen as an across-the-board guaranty. Thus, DMH-11 and India's genome-edited rice varieties should not be regarded as final successes, but as case studies in progress, useful in imagining what sustainable agricultural intensification might look like, if, before wider dissemination, their agronomic performance, environmental effects, biosafety and socio-economic effects are carefully examined.

Oilseeds and the Demand of Genome Editing: A Special Emphasis on Soybean

Soybean, among oilseed crops, holds a unique strategic position as a source of edible oil and high-quality protein. Soybean is cultivated in ~12–13 million ha in India, but the national productivity (~1.2 t ha⁻¹) is much lower than the world average of >3.0 t ha⁻¹ in countries like Brazil and USA (FAOSTAT, 2023).

Conventional breeding in soybean is constrained on several fronts. The cultivated gene pool has a comparatively narrow genetic base, which limits the scope for recombination-based improvement; strong genotype × environment interactions make trait expression - particularly for yield and stress tolerance - difficult to predict and stabilize across India's diverse agro-climatic zones; and susceptibility to major biotic stresses, including charcoal rot (*Macrophomina phaseolina*), Asian soybean rust (*Phakopsora pachyrhizi*), yellow mosaic virus (transmitted by the whitefly *Bemisia tabaci*) and pod-feeding insects, continues to erode both yield and seed quality despite decades of resistance-breeding effort.

Genome editing represents one of several promising pathways for overcoming these barriers. Targeted knockout of susceptibility (S) genes - host genes that pathogens co-opt for infection - may reduce disease development for constraints such as charcoal rot, potentially without the yield drag sometimes associated with classical resistance introgression. Editing of genes controlling oil biosynthesis, particularly fatty acid desaturase genes that regulate oleic acid content, has already been demonstrated to improve the nutritional and industrial quality of soybean oil (see Table 3). Modification of regulatory genes governing drought- and heat-stress signalling may enhance climate resilience, an increasingly relevant requirement for India's largely rainfed soybean belt, although most such applications remain at an early experimental stage.

Recent Indian research efforts, including those led by ICAR, have been directed towards CRISPR-Cas mediated editing of stress-responsive and yield-related genes in soybean. While most of these efforts remain at the experimental stage, the 2022 regulatory exemption has improved the translational prospects of genome-edited soybean varieties. Given India's dependence on edible-oil imports and the ecological constraints on expanding oil palm cultivation across all regions, genome-edited soybean has the potential to become an important component of India's strategy for improving oilseed productivity and reducing import dependence, provided the technical, regulatory and socio-economic challenges discussed later in this review are successfully addressed.

3. Re-orienting GM and GE crops in India's second green revolution

The advent of genome-edited rice, the approval of DMH-11 mustard and the continued progress in soybean genome editing collectively indicate a recalibration of biotechnology strategy in India. India is shifting from a blanket endorsement of transgenic crops to a risk-proportionate regulatory regime based on scientific evidence to decide deployment, rather than a trait-based approach.

This changing landscape requires a shift in the discussion on GM crops in India beyond the narrow framing of Bt cotton and Bt brinjal, and toward the broader range of genome editing enabled solutions in the alignment of productivity, sustainability and public acceptability.

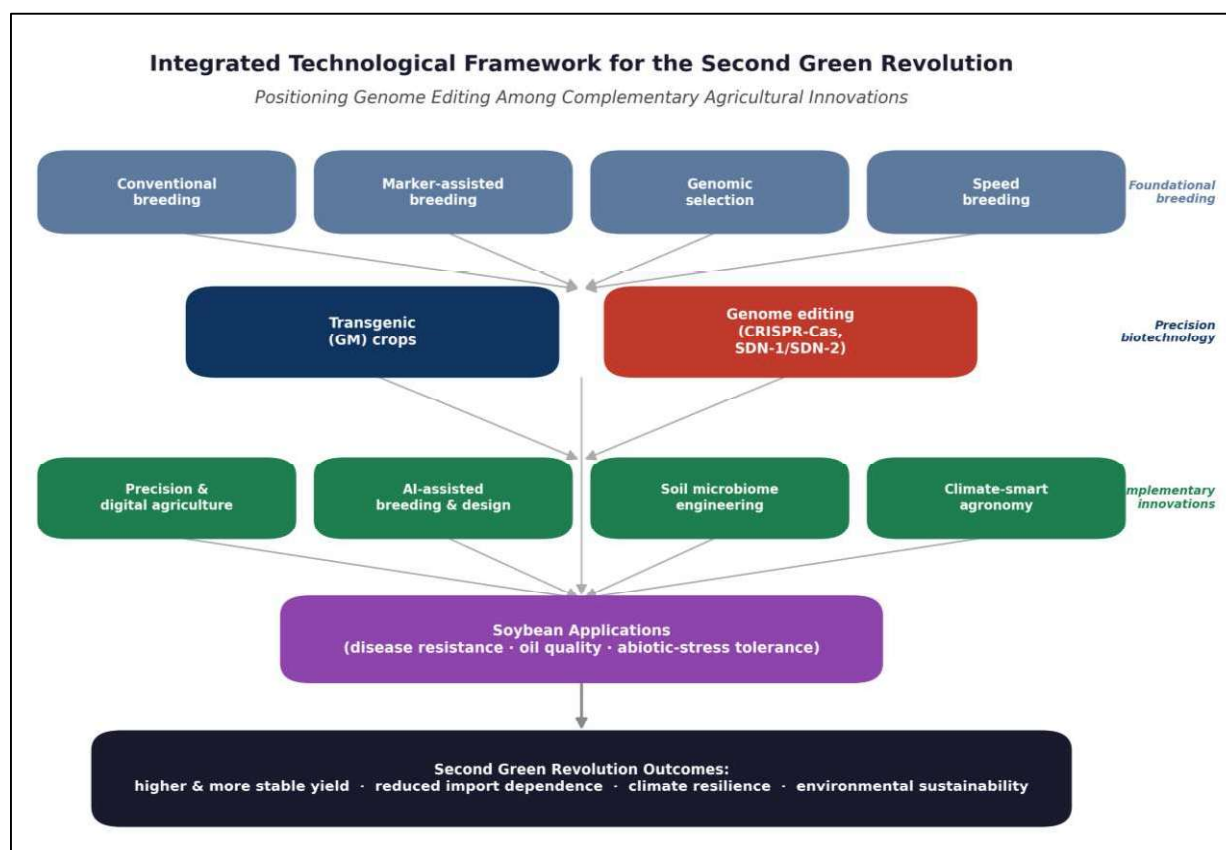


Figure 1. Integrated Technological Framework for the Second Green Revolution

Positioning Genome Editing Among Complementary Agricultural Innovations. Foundational breeding technologies (conventional breeding, marker-assisted breeding, genomic selection, speed breeding) feed into precision biotechnology approaches (transgenic/GM crops and genome editing), which combine with complementary innovations (precision and digital agriculture, AI-assisted breeding and design, soil microbiome engineering, climate-smart agronomy) to enable soybean-specific applications and, collectively, the outcomes sought under the Second Green Revolution. Genome editing is highlighted to show its position within this broader technology portfolio rather than as its sole driver.

Conventional Breeding, GM Crops and Genome Editing: A Comparative Assessment

A direct comparison across conventional breeding, marker-assisted breeding, transgenic GM crops and genome editing clarifies their complementary, rather than competing, roles (Table 2). Conventional breeding remains the most broadly trusted and regulation-free route to trait improvement, but it is comparatively slow - typically 8–15 years per released variety in a self-pollinated crop such as soybean - and is bounded by the genetic diversity present within sexually compatible germplasm. Marker-assisted breeding accelerates this same process without changing its underlying genetic-variation source, using DNA markers to select more efficiently within existing germplasm.

Table 2. Comparative Assessment of Conventional Breeding, Marker-Assisted Breeding, Transgenic (GM) Crops and Genome Editing

Parameter	Conventional breeding	Marker-assisted breeding	Transgenic (GM) crops	Genome editing (SDN-1/2)
Genetic variation source	Existing variation within sexually compatible gene pools	Existing variation, selected more efficiently via markers	Novel genes, including from unrelated species	Existing gene sequence, precisely modified in situ
Precision	Low - whole-genome recombination	Low–Moderate - selection precision, not editing precision	Moderate - insertion site can be imprecise without further screening	High - targets a defined sequence, though not free of off-target risk
Time to release a variety	8–15 years	6–10 years	8–12 years (incl. regulatory review)	3–6 years (technical development); regulatory timeline shorter under SDN-1/2
Regulatory burden (India)	Minimal - not separately regulated	Minimal - not separately regulated	High - full GEAC biosafety review; food crops largely restricted since 2002	Low–Moderate - SDN-1/2 categories exempted from GMO rules (2022 notification)
Public acceptance (India)	High	High	Low–Moderate - persistent controversy outside Bt cotton	Moderate–High - still emerging, generally viewed more favourably than transgenics
Relative cost of variety development	Low–Moderate	Moderate (genotyping costs)	High (transformation, regulatory dossiers, field trials)	Moderate (transformation and screening costs, shorter regulatory path)
Suitability for polygenic/complex traits	High - best suited of the four approaches	High - effective when markers explain sufficient variance	Low - typically single/few-gene traits	Low–Moderate - depends on availability of characterized single-gene targets
Presence of foreign DNA in final product	None	None	Yes, unless subsequently segregated out	None for SDN-1/2 edits (no foreign DNA integrated)
Multiplex capability (editing several targets at once)	Not applicable	Not applicable	Possible but technically demanding	Increasingly routine (multi-gRNA constructs)
Suitability for soybean specifically	Established but slow given narrow genetic base	Established; limited by marker density in some traits	Technically proven globally, but not deployed in Indian soybean	Actively being explored for disease, oil-quality and stress traits (Table 3)

The transgenic GM technology can introduce entirely novel traits, including genes from unrelated species, and has the deepest empirical track record of agronomic and environmental performance among the four approaches; its principal disadvantages are a comparatively long and costly regulatory pathway, dependence in many cases on proprietary technology providers, and continued public

and policy sensitivity in India outside Bt cotton. Genome editing, particularly SDN-1/SDN-2 applications that leave no foreign DNA in the final product, combines much of the precision and speed advantage of transgenic approaches with a regulatory and public-acceptance profile that is closer to conventional breeding, since India's 2022 notification treats such edits as broadly

equivalent to conventionally derived variation. Genome editing's principal limitation, by contrast, is that it depends on the availability of well-characterized single-gene targets and is therefore currently better suited to qualitative, monogenic traits than to complex polygenic traits or to introducing wholly novel gene functions (Table 2).

This comparative positioning - rather than a claim that any one approach supersedes the others - is the basis on which genome editing is treated in this review as the most immediately actionable technology for advancing India's Second Green Revolution, while conventional breeding and, where appropriate, transgenic approaches continue to play complementary roles.

4. LIMITS TO THE FIRST GREEN REVOLUTION

Productive Plateaus and Yield Fatigue

The productivity path of the first Green Revolution has flattened over the last two decades, although impressive gains were achieved. In India, rice yields increased from 2.0 t ha⁻¹ in 1995 to only ~2.7 t ha⁻¹ in 2022 versus >6 t ha⁻¹ in China and >7 t ha⁻¹ in Egypt (FAOSTAT, 2023). Wheat yields have also plateaued at about 3.5 t ha⁻¹ with only marginal gains year-on-year despite higher fertilizer inputs.

This phenomenon is popularly referred to as 'yield fatigue' and is the diminishing marginal returns of input-intensive agriculture. ICAR and CIMMYT's long-term experiments have indicated that factor productivity is declining in rice-wheat systems, especially in north-western India, because of soil nutrient imbalance, micronutrient deficiencies and depletion of soil organic carbon.

Environmental Degradation

The Researchers have thoroughly documented the environmental costs of the First Green Revolution, acknowledged. Nitrate pollution of groundwater, eutrophication of water bodies and increasing greenhouse gas emissions, particularly nitrous oxide (N₂O) are consequences of the over-use of nitrogenous fertilisers. India uses over 35 million tonnes of chemical fertilizers each year, with nitrogen use efficiency less than 40% (FAO, 2021).

The application of pesticides has also increased, although unevenly across crops. Cotton alone historically accounted for nearly 50% of India's pesticide consumption, despite occupying less than 6% of

cultivated land prior to Bt cotton adoption. This chemical dependence has resulted in pest resistance, secondary pest outbreaks, and adverse health impacts on farm workers.

Regional and Social Imbalances

The benefits of the First Green Revolution irrigated regions of north-western India largely reaped the benefits of the First Green Revolution. In irrigated regions of north-western India. Rainfed areas, which constitute more than half of India's agricultural land, saw limited gains. Critical for nutritional security, pulses, oilseeds and millets were neglected resulting in chronic yield gaps and import dependence. "India imports more than 60% of its edible oil requirements, which points to structural weaknesses in crop diversification.

Future agricultural strategy: Implications

These constraints put a question mark over a very different approach to agriculture that combines biotechnology, precision agriculture, climate-smart methods and inclusive policies. GM crops, by addressing biotic and abiotic stresses at the genetic level, offer a pathway to overcome several constraints inherent in conventional input-driven agriculture.

Implications for India's Second Green Revolution

The global evidence base demonstrates that GM crops have delivered consistent agronomic, economic, and environmental benefits across diverse contexts. India's agricultural challenges-yield stagnation, high biotic stress losses, climate vulnerability, and declining factor productivity-closely mirror those of many GM-adopting developing countries. For example, India has 20-30% crop losses annually due to pests, diseases and weeds, despite extensive use of pesticides (ICAR, 2021).

In this context, genetically modified crops should be thought of not only as technologies that enhance yields, but also as tools for risk management and sustainability that can stabilize production in the face of increasing environmental uncertainty. The fact that Bt cotton has continued to be successful is empirical evidence of this role, and the fact that genome-editing initiatives are just getting started suggests that the contribution of biotechnology could potentially expand beyond first-generation transgenic traits.

Complementary technologies are the focus of the second green revolution. Genome editing is most useful as a tool, not as a stand-alone solution, because it is a component

of a larger suite of technologies that are required to achieve the Second Green Revolution. By enabling selection based on predicted breeding values prior to field evaluation, genomic selection and high-throughput phenotyping are contributing to the reduction of breeding cycles during the breeding process. Speed-breeding protocols, using extended photoperiods and controlled environments, can compress several breeding generations into a single calendar year. Digital and precision-agriculture tools - remote sensing, variable-rate input application and AI-based decision-support systems - allow input use to be matched more closely to real-time crop and soil conditions, reducing waste and environmental impact. Microbiome-based technologies, including biofertilizers and biostimulants derived from plant-growth-promoting microorganisms, offer a complementary route to improving nutrient-use efficiency and stress tolerance without additional genetic intervention. Integrating these technologies with genome editing, rather than treating them as separate research tracks, is likely to be necessary for the productivity, resilience and sustainability gains the Second Green Revolution requires; a full technical treatment of each lies beyond the scope of this review and is flagged here as an important direction for future synthesis.

5. OILSEEDS AND THE SECOND GREEN REVOLUTION: STRATEGIC ROLE OF SOYBEAN GENOME EDITING

Among all crop categories, oilseeds represent the most critical and under-addressed constraint in India's agricultural economy. Despite occupying a substantial share of cultivated area, oilseed productivity remains low, and the country's dependence on imports continues to rise. In this context, soybean-India's most widely grown oilseed-emerges as a prime candidate for genome-editing-led transformation.

India's Oilseed Deficit: Structural and Technological Gaps

India currently imports more than 60% of its edible oil requirement, making it one of the world's largest importers of vegetable oils. Soybean is the largest crop contributing to domestic oilseed production but average national yields are only ~1.1–1.3 t ha⁻¹, far below the 3.0–3.5 t ha⁻¹ in large producing countries such as Brazil and the United States (FAOSTAT, 2023).

This yield gap cannot be explained solely through agronomic practices. Conventional breeding in soybean

is limited by structural constraints such as narrow genetic base, high susceptibility to biotic stresses, and strong genotype × environment interactions. These challenges are further compounded with climate variability in rainfed soybean growing regions of central India.

Biological Stress and Soybean Yield Variability in Soybean Production

Insect pests and diseases constrain soybean production in India through several major and regionally variable biotic stresses, including charcoal rot (*Macrophomina phaseolina*), Asian soybean rust (*Phakopsora pachyrhizi*), yellow mosaic virus and collar rot (*Sclerotium rolfsii*), alongside defoliating insect pests. Charcoal rot is generally regarded as the single most damaging of these under India's characteristically hot, moisture-stressed growing conditions, with yield losses exceeding 30–50% under severe drought. Yellow mosaic virus, transmitted by the whitefly (*Bemisia tabaci*), is a comparably serious constraint in northern and central growing tracts in years of high vector pressure, while Asian soybean rust and collar rot cause more sporadic but locally severe losses depending on humidity and cropping-season conditions.

Traditional resistance breeding has met with limited success due to the quantitative nature of resistance and the lack of strong, single-gene resistance sources. This has prompted increasing interest in susceptibility (S) gene-based approaches, where disease development is curtailed by knocking out host genes required for pathogen colonization.

Genome Editing: A Promising Tool for Soybean Improvement

Genome editing provides promising opportunities to address long-standing bottlenecks in soybean improvement. CRISPR-Cas systems allow researchers to precisely edit genes involved in disease susceptibility, stress response and oil biosynthesis, although the maturity of these applications varies considerably by trait (Table 3).

Priority applications include knockout of S genes conferring susceptibility to charcoal rot and rust, editing of fatty acid desaturase genes to enhance oleic acid content, and modification of regulatory genes governing drought- and heat-stress responses.

Table 3. Illustrative Candidate Genome-Editing Targets for Soybean Improvement

Trait	Candidate gene(s)/target class	Editing strategy	Expected phenotype	Current evidence status
Oil quality (high oleic acid)	GmFAD2-1A / GmFAD2-1B (fatty acid desaturase)	CRISPR/Cas9 knockout	Oleic acid increased from ~20% to 80%+	Demonstrated in soybean; commercialized in the U.S. (e.g., Do et al., 2019)
Root/stem rot resistance (<i>Phytophthora sojae</i>)	GmTAP1 (susceptibility gene)	CRISPR/Cas9 knockout	Enhanced resistance to multiple <i>P. sojae</i> races	Demonstrated in soybean (Liu et al., 2023)
Viral disease resistance (soybean mosaic virus and related potyviruses)	eIF4E-family translation-initiation factors (susceptibility genes)	CRISPR/Cas9 knockout (recessive resistance)	Reduced potyvirus susceptibility	Demonstrated in other dicots (e.g., melon, Arabidopsis); a priority target for soybean by analogy, not yet reported in soybean
Isoflavone-mediated viral resistance	GmF3H1, GmF3H2, GmFNSII-1 (flavonoid pathway)	CRISPR/Cas9 multiplex knockout	Elevated isoflavone content, improved SMV resistance	Demonstrated in soybean hairy roots (Zhang et al., 2020)
Pod/seed architecture	JAGGED-family orthologs	Knockout / regulatory editing	Altered pod number and seed-set traits	Established in model and other legume species; soybean-specific validation ongoing
Drought/heat tolerance	NAC-family transcription factors (e.g., GmNAC members)	Editing of stress-responsive regulatory elements	Improved abiotic-stress tolerance	Multiple GmNAC members functionally characterized; editing-based validation at an early experimental stage

Beyond disease resistance and oil quality, additional soybean traits are increasingly being considered for genome-editing intervention, including pod-shattering resistance to reduce pre-harvest yield loss, seed protein content and amino-acid balance to improve feed and food value, and photoperiod/maturity-duration genes to extend soybean cultivation into non-traditional agro-climatic zones. Systematic prioritization of these targets, informed by India-specific genomic resources and multi-location

phenotyping, will be necessary to translate genome-editing capability into deployable soybean varieties. Importantly, such edits will generally be considered SDN-1 or SDN-2 making them eligible for India's streamlined regulatory pathway. This regulatory alignment significantly enhances the translational potential of genome-edited soybean varieties.

The Global Context: GM Soybean as a Benchmark

Soybean is the most widely adopted GM crop worldwide and constitutes almost half of the total GM crop area. Consistent yield stability and profitability have been achieved in major producing countries with herbicide tolerance and stacked traits GM soybean varieties. India has not adopted transgenic GM soybean, but the world experience offers a benchmark to understand the biological feasibility and economic relevance of molecular interventions in this crop. Genome editing may enable more rapid soybean improvement than conventional approaches for selected, well-characterized traits, while complementing rather than replacing existing breeding programmes. Its transgene-free character under SDN-1/SDN-2 also positions it differently, from a policy and public-acceptance standpoint than the transgenic GM crops that have faced regulatory and social resistance in India to date.

Genome editing of soybean and the second green revolution

From a Second Green Revolution perspective, genome-edited soybean addresses multiple national priorities simultaneously: Edible oil self-reliance, climate resilience, farmer income stability, and sustainability. By reducing disease-induced yield losses and improving oil quality, genome-edited soybean can enhance both productivity and value addition.

Additionally, the improvement of soybeans through genome editing is in line with India's focus on Atmanirbhar Bharat in the agricultural sector because it can primarily be driven by research institutions that are supported by the public sector. This results in a decreased reliance on technologies that are imported and improves the nation's capacity in the field of advanced crop biotechnology.

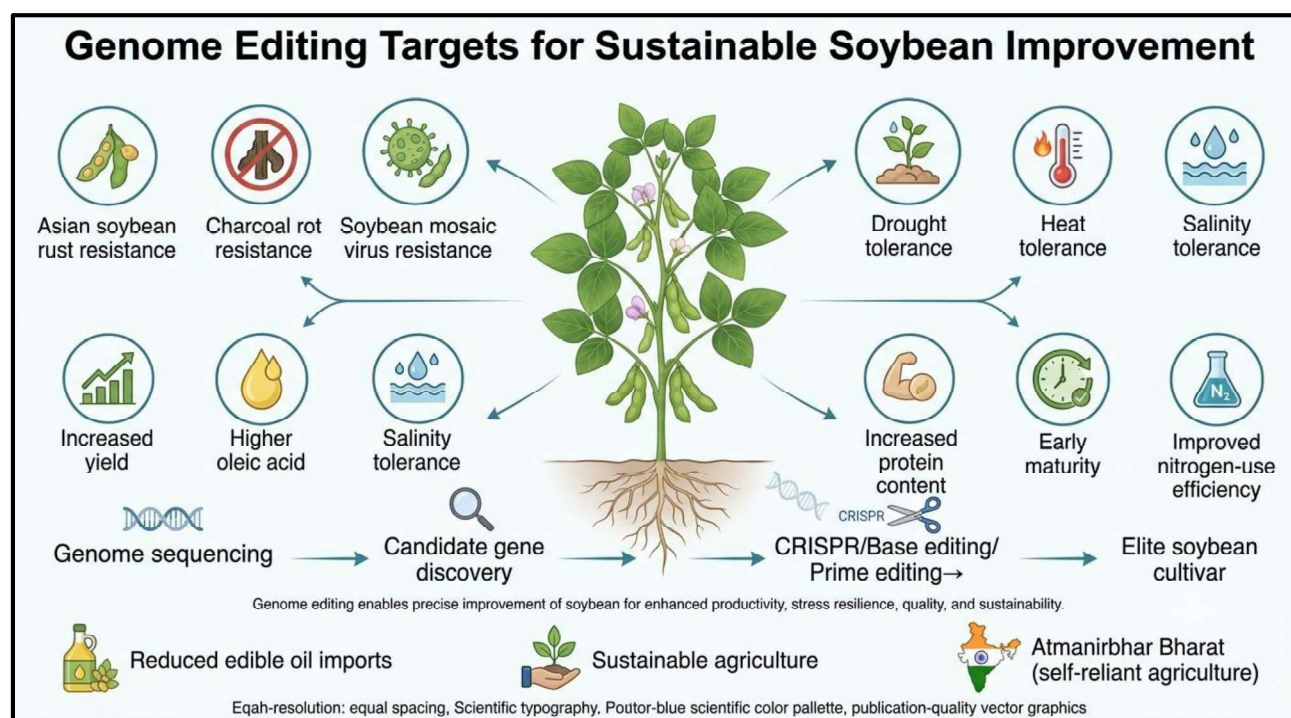


Figure 2. Genome editing targets for sustainable soybean improvement

Policy Readiness and the Path Forward for Soybean Biotechnology

India's present regulatory regime is particularly well positioned to support soybean genome editing. SDN-1 and SDN-2 crops are exempted from GMO regulations,

thereby lowering entry barriers while ensuring scientific oversight. However, successful deployment will require complementary investments in phenotyping, multi-location testing and extension to ensure farmer level impact.

Long-term genome editing in soybean could serve as a useful model for oilseed transformation, illustrating how precision breeding might deliver tangible benefits without sacrificing biosafety or public trust - provided the challenges outlined in the following section are addressed through sustained research investment and transparent governance.

6. CHALLENGES AND FUTURE PERSPECTIVES

A balanced assessment of genome editing's role in India's Second Green Revolution must weigh its opportunities against a substantial set of technical, biological, regulatory and social constraints that remain unresolved. These are discussed below, followed by a forward-looking view of the methodological advances likely to shape the field over the next decade.

Technical and Biological Challenges

At the technical level, off-target mutations remain a concern for any nuclease-based editing system, and rigorous whole-genome sequencing or equivalent validation is required before edited lines can be considered for release. Soybean itself poses a persistent biological bottleneck: it is comparatively recalcitrant to tissue-culture regeneration and *Agrobacterium*-mediated transformation, and transformation efficiency is strongly genotype-dependent, so protocols validated in a reference cultivar such as Williams 82 often transfer poorly to elite Indian genetic backgrounds. Many agronomically important soybean traits - yield, drought tolerance, and durable disease resistance among them - are polygenic and quantitatively inherited, which limits the direct applicability of single-gene knockout strategies and favours approaches that combine editing with genomic selection. Robust multi-location field validation, rather than controlled-environment results alone, is essential before any editing-derived line can be considered agronomically proven, and comprehensive high-throughput phenotyping capacity to support this

validation remains limited in Indian public-sector research. Genotype $\times$ environment interactions add a further layer of complexity, since a trait improvement demonstrated under one set of climatic and management conditions may not translate reliably across India's diverse soybean-growing agro-ecologies.

Regulatory, Economic and Social Challenges

Beyond the technical domain, regulatory frameworks for genome-edited crops remain heterogeneous across countries, which complicates trade, technology transfer and international collaboration even where a given edit is treated as non-GMO domestically. Intellectual-property considerations around CRISPR-Cas core technology and specific trait patents may affect the terms on which public-sector institutions in India can deploy genome-edited soybean at scale. Consumer and public acceptance of genome-edited food crops in India is still forming and cannot be assumed to mirror the comparatively favourable early signals seen for SDN-1/2 categories in policy circles; sustained public communication and transparent risk assessment will be necessary. Broader ethical considerations - including equitable access for smallholder and resource-poor farmers, seed sovereignty, and the risk that public-sector innovation is outpaced or absorbed by private technology providers - also warrant explicit attention in policy design, rather than being treated as secondary to the underlying science.

Future Perspectives

Several methodological advances are likely to shape the next phase of genome-editing research relevant to soybean and to the Second Green Revolution more broadly (Table 4). Base editing and prime editing extend the CRISPR toolkit beyond simple knockouts to precise nucleotide-level changes and small, defined insertions or replacements without double-strand breaks, which may reduce off-target risk and broaden the range of traits that can be engineered. Epigenome editing, which modulates

gene expression without altering the underlying DNA sequence, is an early-stage but potentially powerful complement to sequence-level editing for quantitative traits. Pan-genome-guided design - using structural variation captured across many sequenced soybean accessions, rather than a single reference genome - together with AI-guided guide-RNA design, is expected to improve target selection and reduce off-target prediction error. Deeper integration of genome editing with genome-wide association studies (GWAS) and

genomic selection could shorten the path from candidate-gene discovery to deployable variety, while speed-breeding platforms compress the generations needed to fix and evaluate edited lines. Multi-omics integration and, more speculatively, ‘digital twin’ modelling of crop-genotype-environment interactions may eventually allow some field-performance questions to be explored computationally before physical trials are undertaken, though this remains an emerging rather than an established capability.

Table 4. Emerging Methodologies Relevant to Future Genome-Editing Research in Soybean

Methodology	Description	Relevance to soybean improvement	Maturity
Base editing	Direct chemical conversion of one base pair to another without a double-strand break	Precise correction/introduction of point mutations (e.g., stress-response alleles)	Early-stage in soybean; established in model species and some crops
Prime editing	‘Search-and-replace’ editing enabling small insertions, deletions and substitutions	Fine-tuning regulatory or coding sequences beyond simple knockouts	Early-stage; limited crop-species reports to date
Epigenome editing	Targeted modulation of DNA methylation/chromatin state without sequence change	Potential lever for quantitative traits without altering DNA sequence	Exploratory; largely proof-of-concept in plants
Pan-genome-guided target design	Using structural variation across many sequenced accessions rather than one reference genome	Better capture of soybean's genetic diversity when selecting edit targets	Emerging as soybean pan-genome resources expand
AI-guided gRNA design	Machine-learning prediction of high-efficiency, low-off-target guide RNAs	More reliable editing outcomes, reduced off-target validation burden	Increasingly used alongside standard design tools
Integration with GWAS/genomic selection	Combining association-mapping and genomic-prediction outputs with candidate-gene editing	Prioritizes editing targets most likely to affect complex traits	Growing practice in well-resourced breeding programmes
Speed breeding	Extended photoperiod/controlled-environment cycling to compress generations	Faster fixation and multiplication of edited lines	Established in several crops; limited soybean-specific infrastructure in India
Multi-omics integration	Combined genomic, transcriptomic, proteomic and metabolomic profiling	Mechanistic validation of edited-line phenotypes	Research-stage; concentrated in genomics-capable institutes
Digital twins for crop improvement	Computational models simulating genotype × environment × management outcomes	Potential to prioritize field trials and reduce testing burden	Speculative/early-exploratory in crop science generally

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