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# Recent Advances in Vegetable Breeding in India: Challenges and Prospects

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**ABSTRACT**

Vegetable crops play a crucial role in Indian agriculture, contributing to nutritional security, livelihoods and dietary diversity. In India, vegetable breeding has evolved from conventional hybridisation and pedigree selection to incorporate molecular markers, genomics, gene editing and high-throughput phenotyping. This review summarises recent advances (2023-2025) in vegetable breeding in India, emphasising major breeding objectives (yield, stress tolerance, nutrition), modern tools (marker-assisted selection, genomic selection, CRISPR/Cas editing, speed breeding), and crop-specific case examples (tomato, brinjal, chilli, okra). It highlights persistent challenges such as narrow genetic base, transformation bottlenecks, trait complexity, and seed system constraints and outlines prospects for climate-smart, nutrition-smart and data-driven vegetable breeding in the Indian context. A table summarising key technologies and applications is provided.

***Keywords*: *Vegetable breeding, India, genomics, gene editing, nutritional enhancement, climate resilience***

## Introduction

Vegetables are integral to Indian horticulture, providing vitamins, minerals, phytonutrients, dietary fibre and income opportunities for smallholder farmers. Given the rapidly changing agro-climatic conditions, increasing pest and disease pressures, consumer demand for high-quality and nutritious produce, and the imperative of sustainable production, the necessity for improved vegetable varieties has grown significantly. In India, breeding programmes for vegetables must address multiple concurrent objectives high yield, abiotic and biotic stress tolerance, improved nutrient content, as well as adaptation to small farm realities and resource-limited environments.

Historically, vegetable breeding in India has relied on pedigree selection, hybrid development (often via cytoplasmic male sterility or gynoecy systems), and introgression of major R-genes. However, more recent years (2023-2025) have seen an increasing shift to molecular and genomic tools. For example, a review of trends in vegetable research in India states that "genome editing has opened a new avenue in development of improved lines, however it is just gaining momentum in vegetable research in India.". Further, pre-breeding strategies to widen the genetic base through wild relatives are gaining traction. This review aims to present the current state of vegetable breeding in India, highlight major advances, explore crop-specific applications, discuss challenges and outline future directions relevant to India's horticultural systems.

## Major Breeding Objectives in Indian Vegetable Crops

### Yield and agronomic improvement

In India's small farm systems, improving yield and cropping efficiency remains a primary objective. Vegetable breeding programmes target traits such as early maturity, synchronised fruiting, compact growth for protected cultivation, mechanical harvesting adaptability, and efficient resource use (water, nutrients). For example, many tomato and chilli hybrids released in India focus on high fruit weight, better seed set under high temperature, and uniformity of fruiting.

### Biotic stress resistance

Vegetables grown in India are subject to a wide array of pests (fruit-borer, thrips, whiteflies) and diseases (viral leaf curl, fungal wilts, bacterial rots). Breeding for disease and pest resistance remains critical. Indian programmes have deployed male-sterility systems, gynoecy, and hybrid development for insect/pest resistance. Marker-assisted selection (MAS) is now being used for stacking R-genes in crops such as tomato (Ty-genes for leaf curl), chilli, onion and cauliflower in India.

### Abiotic stress tolerance and climate resilience

With rising temperatures, erratic rainfall, salinity intrusion and drought episodes, vegetables in India require resilience. Breeding programmes are increasingly focusing on heat-tolerance (flower/fruit set under high T), drought/limited water, and salinity tolerance. While many of these efforts remain in early stages for vegetables, the need is compelling given the vulnerability of Indian horticulture to climate shocks.

**Nutritional and phytonutrient quality enhancement**

There is growing consumer and policy demand in India for vegetables with enhanced nutritional value vitamins, minerals, antioxidants, phytonutrients and reduced undesirable compounds (e.g., nitrate in leafy vegetables). For instance, breeding strategies to reduce nitrate accumulation in vegetables have been reviewed by Indian scientists. Bio-fortification of vegetables (for vitamin C, lycopene, anthocyanin) is becoming part of breeding objectives as well.

**Resource-efficient and sustainable production**

An emerging objective is breeding vegetables that perform under reduced inputs (fertiliser, water), compatible with protected cultivation and organic systems. This aligns with national goals of sustainable intensification of horticulture. The use of doubled haploids, rapid cycle breeding and speed breeding (though still nascent in India's vegetables) further contribute to shortening varietal development cycles.

## Modern Breeding Tools and Technological Advances

**Marker-assisted selection (MAS) and genomic selection (GS)**

MAS has become more routinely used in Indian vegetable breeding: Pandey et al. (2024) document that MAS for tomato leaf curl (Ty1/Ty3/Ty5 etc), onion male sterility, cauliflower black rot resistance and chilli heat tolerance has been undertaken in India. However, GS (genome-wide prediction) remains underutilised in Indian vegetable breeding programmes despite its advantages for complex quantitative traits.

**Gene editing (CRISPR/Cas and derivatives)**

Globally vegetable breeding is leveraging genome editing, and though in India this application is still in its infancy for vegetables, the review of trends mentions that "genome-editing has opened a new avenue however it is just gaining momentum in vegetable research in India." As transformation and regulatory frameworks mature in India, gene editing will become a powerful tool to modify key genes (e.g., fruit softening, stress responses, phytonutrient pathways) in vegetable crops.

**High-throughput phenotyping, omics and AI integration**

High-throughput phenotyping (phenomics) is increasingly used globally and is beginning to find application in Indian horticulture. Coupled with genomics, transcriptomics, proteomics and metabolomics, these multi-omics approaches hold promise for dissecting complex traits such as heat tolerance or nutrient accumulation. Data-driven approaches, including machine learning and AI, although still emerging in Indian vegetable breeding, are set to accelerate trait prediction and selection.

**Speed breeding, doubled haploids and rapid generation advancement**

To reduce breeding cycle time, speed-breeding protocols (extended photoperiod, controlled environment) and doubled haploid technologies (for rapid homozygosity) are being explored. Globally, "Speed Breeding 3.0: mainstreaming light-driven plant growth" is a recent review. In India, while vegetables are more challenging, adapting these technologies could shorten times to release new varieties.

**Pangenomics, germplasm diversity and pre-breeding**

Exploiting wild relatives and landraces is critical for broadening the genetic base. Pre-breeding efforts aim to introgress genes from wild relatives for stress tolerance and quality traits. Indian vegetable breeding is increasingly investing in pre-breeding and germplasm utilisation. Pangenome assemblies and SNP array resources, although more advanced in cereals, are gradually being applied to horticultural crops.

## Crop-Specific Case Examples in Indian Vegetable Breeding

**Tomato (*Solanum lycopersicum*)**

Tomato is a major vegetable crop in India. Recent breeding efforts have focused on high fruit weight, synchronous fruiting, heat tolerance, extended shelf-life, and resistance to leaf curl, bacterial wilt and other pathogens. Indian programmes have employed MAS to stack Tygenes (Ty1/Ty3) for tomato leaf curl resistance. Although specific gene editing reports in Indian tomato breeding are limited, global precedents suggest that Indian breeders can target genes controlling fruit softening, parthenocarpy, pigment accumulation, and stress responses. Integration of protected-cultivation hybrids and greenhouse-adapted genotypes is also an active area.

**Table 1. Summary of Key Breeding Technologies and Their Application in Indian Vegetables**

| Technology | Application in Indian Vegetable Crops | Key Benefit |
|---|---|---|
| **Marker-Assisted Selection (MAS)** | Stacking R-genes in tomato (Ty1/Ty3), cauliflower, onion male sterility. | Faster introgression of target genes |
| **Genomic Selection (GS)** | Emerging, not yet widely adopted in Indian vegetables | Predict complex traits early |
| **Gene Editing (CRISPR/Cas)** | Early stage in India; global models show fruit quality, stress traits modification | Precision trait improvement |
| **High-Throughput Phenomics / AI** | Starting to be used for phenotyping under stress/quality traits | Better trait-genome linkages |
| **Speed Breeding / DH** | Under exploration in vegetables in India | Reduce breeding cycle time |
| **Pre-Breeding / Wild-Relatives** | Introgression for stress/resistance traits, broaden diversity | Expand genetic base |

**Brinjal (Eggplant, Solanum melongena)**

Brinjal (eggplant) is widely grown in India, but productivity is constrained by pests (shoot/fruit borer), bacterial wilt and other stresses. Conventional hybrid development using cytoplasmic male sterility has been extensively applied. Recent reviews note that bio-fortified brinjals and anthocyanin-rich types are being considered. Wider use of molecular tools is expected to accelerate brinjal improvement.

**Chilli (*Capsicum* spp.)**

Chilli is another key vegetable/spice crop in India. Recent breeding aims include heat tolerance, high capsaicin/pungency indices, improved fruit shape, and resistance to leaf curl virus, thrips and powdery mildew. MAS is being used to some extent for chilli but further adoption of GS and gene editing could speed progress.

**Okra / Leafy Vegetables**

In okra, breeding goals in India include virus resistance (e.g., Yellow Vein Mosaic Virus), fibre reduction, improved yield in hot/dry climates, and suitability for protected cultivation. For leafy vegetables, reducing nitrate accumulation and enhancing phytonutrient content are emerging objectives. On reducing nitrate levels in vegetables highlights breeding and biotechnological strategies relevant to India.

**Broad Horticultural Vegetables**

Beyond these, vegetables such as cucurbits (pumpkin, bottle-gourd, bitter-gourd), leafy amaranth, and tuberous/underground vegetables are seeing breeding attention for climates, pest-disease complexes and nutritional enhancement. The review of trends and developments in vegetable research in India notes that over the last five decades around 587 vegetable varieties/hybrids have been released in India under the All India Coordinated Research Project on Vegetable Crops (AICRP-VC).

**Challenges in Vegetable Breeding in India**

**Narrow genetic base and germplasm bottlenecks**

One major challenge is the narrowing of the genetic base in many vegetable crops due to repeated use of elite lines and hybrids. Many traits of interest (resistance, abiotic stress tolerance, nutritional quality) often reside in wild relatives or landraces that are under-utilised. Pre-breeding efforts are still limited and need significant investment.

**Transformation and editing bottlenecks in recalcitrant species**

Many vegetable crops in India (e.g., onion, garlic, certain cucurbits) are recalcitrant to transformation/regeneration or have complex polyploidy, making gene editing or transgenic approaches difficult. Regulatory, institutional and infrastructure constraints further delay adoption of advanced tools. -

### Complexity of traits and environment × genotype interactions

Traits such as abiotic stress tolerance (heat, drought, salinity), nutrient accumulation and shelf-life are complex, polygenic and influenced strongly by environment. Accurate phenotyping, multi-location trials and modelling genotype × environment interaction remain bottlenecks for Indian vegetable breeding programmes.

### Seed system, varietal replacement and adoption issues

Even when improved varieties exist, adoption may be slow. Seed and varietal replacement rates in India remain sub-optimal for vegetables. An article by (2024) reviewed this issue in India's seed system. Further, farmers' preferences (taste, local adaptation, market acceptability), post-harvest handling, and linkage to markets also influence the impact of breeding efforts.

### Integration of multidisciplinary tools and capacity gaps

While high-throughput phenotyping, omics, AI/ML tools are available globally, their penetration in Indian vegetable breeding is still limited. Capacity, infrastructure, training and data management are constraints. Bridging the gap from technology to field applications remains a challenge.

## Future Prospects and Way Forward

### Climate-smart and nutrition-smart breeding

Given the dual need for resilience and nutrition in Indian horticulture, future breeding must emphasise climate-smart (heat, drought, salinity tolerance) and nutrition-smart (enhanced vitamins, minerals, phytonutrients, reduced antinutrients) vegetables. Breeders should adopt "nutritional target" frameworks in variety development, linking breeding with nutritional outcomes.

### Data-driven breeding and digital tools

The integration of high-throughput phenotyping, genomics, AI/ML predictive tools and speed-breeding protocols offers enormous potential. Indian vegetable breeding programmes should invest in phenomic platforms, image/remote sensing, predictive analytics and digital breeding pipelines. For speed breeding, light-driven strategies are now mainstreaming globally and can be adapted to Indian conditions.

### Strengthening germplasm and pre-breeding pipelines

Expanding germplasm repositories, engaging with wild relatives, establishing pre-breeding pipelines and deploying pangenomics/SNP arrays will broaden the gene pool for future breeding. Collaborative networks (national and international) can expedite access to novel alleles and accelerate trait introgression.

### Capacity-building, institutional partnerships and policy support

Enhancing capacity in molecular breeding, bioinformatics, high-throughput phenotyping and data science is essential. Public–private partnerships, inclusion of smallholder farmers and stakeholder-driven breeding (demand-driven) will increase adoption. Policy frameworks to support faster release of gene-edited varieties, stronger seed systems, and seed-village models for vegetables can amplify impact.

### Rapid varietal replacement and market-oriented breeding

Breeding programmes must focus on farmer/consumer-oriented traits (taste, appearance, shelf-life, nutritional value) and ensure rapid varietal replacement. Adoption of improved varieties in the field should be accelerated through extension, demonstration plots, seed availability and linkage with markets. Varietal replacement in vegetables is key for productivity and quality enhancement.

## Conclusion

Vegetable breeding in India is at an inflection point. From conventional methods, the discipline is rapidly moving towards genomics, gene editing, high-throughput phenotyping and data-driven breeding albeit with significant challenges. The breeding objectives now encompass yield and agronomic improvement, biotic and abiotic stress tolerance, nutritional quality, resource efficiency and sustainability. Indian vegetable breeding programmes have begun harnessing technologies such as MAS, CRISPR/Cas (in early stage), speed breeding, and pre-breeding with wild relatives. However, to fully realise the potential of these tools, Indian programmes must overcome bottlenecks such as narrow genetic bases, trait complexity, limited adoption, seed system shortcomings and capacity constraints. Looking ahead, the emphasis should be on climate-smart and nutrition-smart vegetable breeding, backed by strong institutional partnerships, data-enabled tools, broad germplasm access, and farmer-centric markets. As India strives to meet the twin challenges of nutritional security and climate change, delivering improved vegetable varieties that are resilient, nutritious and adoptable will play a pivotal role in the future of Indian horticulture.

## References


- Parveen, R., Kumar, M., Swapnil, Singh, D., Shahani, M., Imam, Z., & Sahoo, J. P. (2023). Understanding the genomic selection for crop improvement: Current progress and future prospects. Molecular Genetics and Genomics, 298(4), 813–821. https://doi.org/10.1007/s00438-023-02026-0

- Kumar, R., Das, S. P., Choudhury, B. U., Kumar, A., Prakash, N. R., Verma, R., Mishra, V. K. (2024). Advances in genomic tools for plant breeding: Harnessing DNA molecular markers, genomic selection, and genome editing. Biological Research, 57, 80. https://doi.org/10.1186/s40659-024-00562-6
- Sagar, P., Srinivasulu, B., & Vamsi, B. (2024). The impact of pre-breeding on vegetable crop improvement: A review. Journal of Experimental Agriculture International, 46(8), 268–282. https://doi.org/10.9734/jeai/2024/v46i82704
- Pandya, M. M., Acharya, R. R., Patel, N. A., Kathiria, K. B., Bhanvadia, A. S., Gohil, D. P., Joshi, V. I. (2024). Development of clustered fruiting and high-yielding variety in brinjal (Solanum melongena L.) through applied plant breeding. Journal of Advances in Biology & Biotechnology, 27(8), 133–144. https://doi.org/10.9734/jabb/2024/v27i81128
- Weiss, J. (2025). Enhancing nutritional quality in vegetables through breeding under protected conditions: Classical and advanced strategies. Science of the Total Environment. (In press). https://doi.org/10.1016/j.scitotenv.2024.xxx
- Nehra, M. R., & Verma, M. (2025). Chemical and molecular advances in vegetable breeding: From genomics to nutritional enhancement. Chemical & Biological, 14(55). https://doi.org/10.37273/chesci.cs232056081
- Roychowdhury, R., et al. (2025). Advancing vegetable genetics with gene editing. [Journal to be updated once published]. https://pubmed.ncbi.nlm.nih.gov/39891757/
- Gong, C., et al. (2025). Artificial intelligence in vegetable crops: Recent advances in phenotyping, genomics and intelligent production. Vegetable Research, 2(5), 0012. https://doi.org/10.48130/vegres-0025-0012
- Mangal, V., et al. (2024). Triumphs of genomics-assisted breeding in crop improvement. Heliyon, 10, e11544. https://doi.org/10.1016/j.heliyon.2024.e11544
- Ramesh Babu, R., Baishya, L. K., Gopala Krishna Reddy, A., Pongener, A., Raghavendra, H. R., & Naik, O. (2024). Climate change effects on sustainable vegetable production in India: A review. International Journal of Environment and Climate Change, 14(3), 804–814. https://doi.org/10.9734/ijecc/2024/v14i34089