

Chemical and Molecular Advances in Vegetable Breeding: From Genomics to Nutritional Enhancement

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Abstract

Vegetable breeding has played a pivotal role in increasing global food production, improving nutrition, and ensuring sustainability. This review provides an overview of recent strategies, technologies, and prospects in vegetable breeding. It highlights progress in hybrid breeding, molecular breeding techniques, marker-assisted selection (MAS), genomic selection (GS), genetic modification (GM), and CRISPR/Cas9 genome editing. Special emphasis is given to yield improvement, pest and disease resistance, nutritional quality, postharvest traits, and abiotic stress tolerance. The role of next-generation sequencing (NGS), bioinformatics, and high-throughput phenotyping is also discussed. Case studies of successful varieties such as Pusa Hybrid tomato, Pusa Purple Long brinjal, and Pusa Snowball cauliflower demonstrate the practical outcomes of breeding programs. The review also highlights challenges including genetic diversity bottlenecks, ethical concerns of GM crops, and socio-economic constraints for smallholder farmers. Future prospects include climate-smart breeding, sustainability-oriented approaches, and public-private collaborations.

Keywords: Abiotic stress, CRISPR/Cas9, genetic modification, hybrid breeding, marker-assisted selection, nutritional quality, vegetable breeding, yield improvement

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Introduction

Vegetables are essential components of the human diet due to their nutritional, medicinal, and economic importance. Globally, vegetable production has increased substantially over the last five decades, supported by breeding innovations [1]. However, the demand for vegetables continues to rise due to population growth, urbanization, and health awareness. Breeding has made significant contributions in developing high-yielding, disease-resistant, and climate-resilient vegetable cultivars [2, 3].

Despite progress, vegetable breeding faces challenges such as biotic and abiotic stresses, limited genetic diversity in elite cultivars, and climate change. These constraints demand innovative approaches integrating traditional and modern breeding technologies to meet global food and nutritional security goals [4].

Breeding Hybrids and Modern Approaches

Hybrid breeding has been a cornerstone in vegetable crop improvement, offering heterosis for yield and resilience. Traditional inbreeding and cross-breeding methods remain foundational [5]. However, contemporary approaches such as marker-assisted selection (MAS), genomic selection (GS), transgenics, and CRISPR/Cas9 gene editing are revolutionizing breeding programs [6, 7]. MAS accelerates the breeding process by tagging desirable genes with molecular markers. GS allows prediction of breeding values using genome-wide information. Genetic modification (GM) enables incorporation of traits such as pest resistance and enhanced nutrition. CRISPR/Cas9 provides precise genome editing for targeted trait improvement, reducing linkage drag.

Crucial Features in Vegetable Breeding

Key breeding targets include

- Yield improvement: Enhanced photosynthetic efficiency, resource use efficiency, and hybrid vigor [8].

- Disease and pest resistance: Resistance to powdery mildew, bacterial wilt, aphids, and blight [9]. Nutritional quality: Enrichment of micronutrients such as iron, carotenoids, and vitamin C [10].
- Abiotic stress tolerance: Development of drought, salinity, and temperature stress-tolerant cultivars [11].
- Postharvest quality: Breeding for extended shelf-life, transportability, and storage.

Technological Developments in Vegetable Breeding

- Modern breeding relies heavily on integration of genetic and computational tools:
- Germplasm conservation: Genetic resource banks ensure a wide gene pool [12].
- Next-Generation Sequencing (NGS): Allows rapid identification of genes linked to desirable traits.
- Bioinformatics: Facilitates large-scale data management and predictive analysis.
- High-throughput phenotyping: Sensor-based and image-analysis systems accelerate field evaluation.

Challenges in Vegetable Breeding

- Limited genetic diversity: Narrow genetic bases restrict breeding gains.
- Public perception and regulations: GM crops face ethical and legal scrutiny [13].
- Climate change: Erratic rainfall, heat waves, and new pest dynamics affect crop success.
- Economic barriers: Smallholder farmers often lack access to advanced breeding products.

Case Studies of Successful Varieties in India

Improvements in fruit quality attributes and resistance to bacterial wilt and early blight are examples of tomato breeding advancements.

Varieties of hybrid tomatoes, such as "Pusa Hybrid"

- The goal is to create a disease-resistant hybrid tomato cultivar with a high yield.
- Breeding Facility: New Delhi's Indian Agricultural Research Institute (IARI).
- A major accomplishment has been the creation of hybrid cultivars like "Pusa Hybrid," which provide enhanced production potential and greater resistance to diseases like bacterial wilt and early blight.

Variety	Yield (tons/ha)	Disease Resistance	Key Benefit
Pusa Hybrid	30-35	Bacterial wilt and early blight	High yield, better disease resistance, suitable for varied climatic conditions

Brinjal (Eggplant) - 'Pusa Purple Long'

- Goal: Create a high-yielding, early-maturing brinjal cultivar with superior fruit quality.
- Key Success: 'Pusa Purple lengthy' is a high-yielding variety that resists pests like the brinjal shoot and fruit borer (BSFB) and has lengthy fruits with no bitterness.

Variety	Yield (tons/ha)	Key Characteristics	Pest Resistance
Pusa Purple Long	30-35	Long,non-bitter fruits	Brinjal shoot and fruit borer

Cauliflower - 'Pusa Snowball'

- Objective: Develop a cauliflower variety that can be grown in a wide range of climates and offers early maturation.
- Breeding Institution: IARI, New Delhi.
- Key Success: 'Pusa Snowball' is one of the most successful cauliflower varieties grown across India, offering good head formation and resistance to diseases like downy mildew.

Variety	Yield (tons/ha)	Disease Resistance	Head Quality
Pusa Snowball	18-22	Downy mildew and leaf blight	High -quality head

Chili Pepper - 'Pusa Jwala'

- Objective: Improve the pungency, yield, and disease resistance of chili peppers.
- Breeding Institution: IARI, New Delhi.
- Key Success: 'Pusa Jwala' is widely known for its high pungency and productivity, and its adaptability to different growing regions across India. It also offers better resistance to pests like the chili wilt.

Variety	Yield (tons/ha)	Pungency	Pest Resistance
Pusa Jwala	8-10	High (more than 1% capasaicin)	Chilli wilt and aphids

Cucumber - 'Pusa Sanyog'

- Objective: Develop a cucumber variety with high resistance to diseases and suitable for year-round production.
- Breeding Institution: IARI, New Delhi.
- Key Success: 'Pusa Sanyog' is a high-yielding variety, resistant to diseases like downy mildew, and produces high-quality, tender fruits.

Variety	Yield (tons/ha)	Fruit quality	Disease Resistance
Pusa Sanyog	20-25	Smooth,tender fruits	Downy mildew, powdery mildew

Okra (Ladyfinger) - 'Pusa Sawani'

- Objective: Develop a high-yielding, disease-resistant okra variety with improved quality.
- Breeding Institution: IARI, New Delhi.
- Key Success: 'Pusa Sawani' is a short-duration, high-yielding variety with reduced spines, making it easier to harvest.

Variety	Yield (tons/ha)	Key Characteristics	Harvest Duration
Pusa Sawani	15-20	reduced spines, smooth texture	50-55 days

Pea - 'Pusa Pragati'

- Objective: Develop a high-yielding, early-maturing pea variety with better disease resistance.
- Breeding Institution: IARI, New Delhi.
- Key Success: 'Pusa Pragati' offers high yields, early maturity, and good resistance to diseases like powdery mildew.

Variety	Yield (tons/ha)	Maturity Duration	Disease Resistance
Pusa Pragati	10-15	55-60 days	Powdery mildew, blight

Spinach - 'Pusa Bharti'

- Objective: Develop spinach varieties with high nutritional content, better taste, and disease resistance.
- Breeding Institution: IARI, New Delhi.
- Key Success: 'Pusa Bharti' is a high-yielding, disease-resistant spinach variety that is rich in iron and other nutrients.

Variety	Yield (tons/ha)	Key Nutrient Content	Disease Resistance
Pusa Bharti	20-25	High in Iron, Vitamin-A	Downy mildew, rust

Carrot - 'Pusa Kesar'

Objective: Develop a carrot variety with better taste, high beta-carotene content, and resistance to diseases.
Breeding Institution: IARI, New Delhi.
Key Success: 'Pusa Kesar' has high beta-carotene levels, making it an excellent choice for improving nutrition, especially in areas with vitamin A deficiency.

Variety	Yield (tons/ha)	Beta-carotene Content	Disease Resistance
Pusa Kesar	25-30	High (rich in beta-carotene)	Root rot, leaf spot

Cabbage breeding

Creating cultivars with longer shelf lives and resistance to pests.

Carrot Breeding

Advances in breeding for increased disease resistance and carotenoid content. These examples demonstrate the integration of conventional and modern breeding to deliver farmer-preferred varieties.

Future Prospects

- The future of vegetable breeding is linked with:
- Climate-smart breeding: Developing cultivars resilient to unpredictable climate conditions [14].
- Sustainability-oriented breeding: Reducing pesticide dependence through resistant varieties.
- Public-private partnerships: Collaboration between government, academia, and private sector for wider adoption.
- Nutritional biofortification: Targeting hidden hunger through enhanced micronutrient density.

Conclusion

Vegetable breeding has significantly contributed to food and nutritional security by improving yield, quality, and stress resilience. Indian success stories such as Pusa Hybrid tomato and Pusa Kesar carrot illustrate how breeding impacts livelihoods and nutrition. Future breeding strategies must integrate advanced molecular tools, climate-smart approaches, and sustainable practices to ensure global food security in the face of climate change.

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