*Plant Archives* Vol. 26, No. 1, 2026 pp. 483-493 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.no.1.067

# RECENT ADVANCES IN BIOTECHNOLOGICAL INTERVENTIONS FOR GENETIC IMPROVEMENT OF HORTICULTURAL CROPS: A REVIEW

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(Date of Receiving-13-12-2025; Date of Revision-31-01-2026; Date of Acceptance-24-02-2026)

## ABSTRACT

Horticultural crops, which include fruits, vegetables, ornamentals, medicinal and aromatic plants, play a vital role in human nutrition, the world economy, and environmental sustainability. But they face growing threats to productivity and quality from climate variability, biotic stresses, lengthy breeding cycles, and limited genetic stocks. Traditional breeding, although essential, is limited by biological constraints such as long juvenile periods, polyploidy, heterozygosity and complex polygenic quality characteristics. Breakthroughs in biotechnology have revolutionized horticultural crop enhancement enabling accurate, fast and scalable approaches. Molecular markers, marker-assisted selection (MAS) and genomic selection (GS) are advancing trait identification and early selection, also in complex or quantitative traits. Tissue culture, micropropagation and somatic embryogenesis contribute to the production of disease-free planting material and play a vital role in transformation and genome editing pipelines. Genome editing tools, with the CRISPR/Cas systems at the forefront, have opened the door to targeted, transgene-free edits to improve fruit quality, stress tolerance, disease resistance in important crops (e.g. tomato, banana, citrus, grape, apple) or for other desired traits. Moreover, development of multi-omics (genomics, transcriptomics, proteomics, metabolomics) integrated with high-throughput phenotyping and artificial intelligence has further improved predictive breeding and precision horticulture. Novel approaches including nanoparticle-based gene delivery and ribonucleoprotein (RNP) platforms present promising alternatives for DNA-free editing. Transformation efficiency, regeneration bottlenecks, data integration, regulatory heterogeneity, and socio-economic aspects remain challenging, despite enormous advances. In general, biotechnology presents a useful framework to develop robust, high yielding and quality improved horticultural cultivars for the potential future climate and market scenarios.

***Key words-*** Horticultural crops; Biotechnology; Marker-assisted selection; Genomic selection; Tissue culture; Micropropagation

## Introduction

Horticultural produce, such as fruits, vegetables, flowers, medicinal and aromatic plants, is crucial for ensuring food security worldwide, strengthening the economy, and enhancing human well-being. They are also important sources of essential nutrients, including vitamins, minerals, antioxidants, and phytochemicals, which play a significant role in well balanced diets and the prevention of many chronic diseases (Ahmed *et al.*, 2024). Globally, the horticulture industry provides livelihood for millions of smallholder farmers and is the backbone of rural economy through intensive production of high-value commodities (FAO, 2023). Vegetable oilseeds are an important horticultural crop although their share in global agricultural Gross Domestic Product (GDP) is much lower, but their contribution is increasing in the production and trade over the past decade (FAO, 2023). In addition to nutrition and economy, horticulture also has ecological and cultural importance, particularly through the maintenance of wild biodiversity in a range of agro-ecological regions and comprises raw materials for the food, cosmetic and pharmaceutical industries (Jaenicke and Virchow, 2016). Yet their productivity and quality are being endangered by rising climate unpredictability, biotic pressures, and environmental degradation, which necessitates innovative approaches for breeding stress-tolerant, high-yielding, and nutritionally superior cultivars (Lal *et al*., 2023).

## Constraints of Traditional Breeding in Horticulture

Conventional breeding (hybridization followed by selection) has been responsible for many horticultural crop improvements over years. However, there are some inherent biological and technical barriers that limit their utility. Numerous fruits and tree crops have long juvenile stages, which postpone the testing and selection of high quality genotypes (Shivran *et al*., 2022). Sexual incompatibility, polyploidy and heterozygosity also make breeding difficult in banana, citrus and grape. Repeated use of elite germplasm has caused the narrowing of the genetic base of many commercial cultivars, which in turn makes them susceptible to pest, disease and abiotic stresses (Salgotra and Chauhan, 2023).

Traits such as flavor, color and content of nutritional compounds are typically influenced by many genes and the environment, which renders their breeding slow and unpredictable (Gaikwad *et al*., 2020). Conventional breeding also involves multiple backcrossing and selections over generations and is laborious and expensive especially in perennials where breeding cycles can be more than a decade long. Hence, to address these limitations, advanced biotechnological approaches are being extensively applied in horticultural improvement programs (Rane *et al*., 2025).

## Biotechnology for Horticultural Improvement

Biotechnology is well suited to complement conventional breeding by facilitating precise genetic modification, by speeding up selection and by enabling the transfer of pleasing trait(s) among crossable species (sexual barriers) (Ma *et al*., 2023). The use of plant tissue culture, molecular markers, genomic selection (GS), genetic engineering in the form of transgenics and genome editing has brought about a paradigm shift in horticultural crop improvement through shortening of the breeding cycle and increasing trait specificity (Xu *et al*., 2019).

The combination of marker assisted selection (MAS) and genomic selection (GS) allows breeders to discover and select the best genotypes using only DNA profiles and this reduces the reliance on phenotypic selection and environmental variability (Xu and Crouch, 2008). In a like manner, the application of tissue culture and micropropagation have been vital in producing disease-free and true-to-type planting materials in banana, potato, strawberry, and ornamental plants (Malabadi *et al*., 2025). In addition, these techniques have contributed to *in vitro* mutagenesis and somaclonal variation, a source of new genetic variation for crop enhancement (Ferreira *et al*., 2023).

One promising development in the recent past has been the use of genome editing tools with a focus on CRISPR/Cas systems, which enable site-specific alterations in genes involved in quality, resistance and stress tolerance (Martín-Valmaseda *et al*., 2023; Ma *et al*., 2023). CRISPR-mediated genome editing has been already successfully used in a number of horticultural crops such as tomato, banana, citrus, grape, apple and strawberry for the improvement of disease resistance, ripening and nutritional quality, etc. (Ramirez-Torres *et al*., 2021). These instruments are having a profound impact on the length of breeding cycles and are making possible “precision horticulture” that involves the manipulation of specific alleles without disturbing the rest of the genome.

## Integration of Omics and Data- driven Approaches

The development of high-throughput sequencing and omics techniques, such as genomics, transcriptomics, proteomics, metabolomics and phenomics, have extended the scope of horticultural biotechnology (Cheng *et al*., 2024). Those platforms also produce large amounts of data that contribute to the identification of candidate genes and regulatory networks associated with quality attributes, including flavor, color, aroma, and stress resilience (Ezra and Carmi, 2025). Multi-omics integration in conjunction with bioinformatics and artificial intelligence (AI)-driven models has allowed for data-driven trait prediction and selection, thus assisting breeders in predicting outcomes earlier within the breeding cycle (Cheng *et al*., 2024).

In addition, nanotechnology-based approaches and futuristic delivery systems, including nanoparticle-based gene delivery and ribonucleoprotein (RNP) complexes, are being investigated for enhancing transformation efficiency and minimizing reliance on conventional Agrobacterium-mediated approaches (Rai *et al*., 2015). These advancements could potentially allow genetic enhancement to be more effective, less costly, and publicly acceptable by circumventing transgenic DNA insertion.

## Transition from Laboratory to Field and Commercialization

Over the past ten years, the application of biotechnology to horticultural crops has gone from laboratory research to field-testing and, in some parts of the world, commercial release of transgenic cultivars. Such as non-browning mushrooms and disease resistant tomatoes developed by genome editing are in field testing stage and in some cases they have been approved by regulatory (Ma *et al*., 2023). Likewise, propagation protocols based on tissue cultures have been commercialized for large scale production of disease free planting materials in crops like banana, sweet potato, and flowers (Xu *et al*., 2019).

## Overview of Biotechnological Tools and Their Roles

This section gives an overview of the major horticultural biotechnological tools with short descriptions, important benefits/drawbacks, and application (focused on fruit and vegetable crops).

### Molecular markers, Marker-Assisted Selection (MAS) & Genomic Selection (GS)

- Molecular markers (i.e., SSRs- Simple Sequence Repeats, SNPs- Single Nucleotide Polymorphisms) are DNA-based loci that exhibit polymorphism and can be associated with traits of interests.
- Marker Assisted Selection (MAS) exploits such markers for the selection of individuals carrying the favorable alleles (quality, resistance) regardless or besides to the phenotypic screening. For major effect genes/QTLs (Collard and Mackill, 2008).
- Genomic Selection (GS) takes this a step further to utilize genome wide marker information (hundreds/thousands of markers) in combination with prediction models to select individuals for complicated quantitative traits (polygenic), with a potential to reduce breeding cycles.

### Advantages

- MAS can lead to a faster breeding by facilitating early selection at seedling stage, decreasing number of plants to phenotype, increasing accuracy (Singh *et al*., 2025).
- GS enables the selection for complex traits (e.g., yield, quality traits) and not only for simple major gene traits.
- These tools are of particular value in horticultural crops with long generation times such as fruit trees and also for vegetatively propagated crops.

### Limitations/Challenges

- The efficiency of MAS relies on a strong marker–trait association (e.g. causal gene or very tightly linked marker). Marker–trait associations should be confirmed in the target population (Teli *et al*., 2025).
- GS involves extensive training populations, reliable phenotypic and genotypic data, and the uptake may be limited in horticulture as compared to major field crops (Teli *et al*., 2025).
- Cost, infrastructure (genotyping platforms) and bioinformatics capacity may constrain adoption in certain areas..

### Applications in horticulture

- SSR/AFLP/SNP markers in fruits and vegetables for disease resistance and quality traits (such as seedlessness, sugar/acid ratio) have been reviewed (Singh *et al*., 2025).

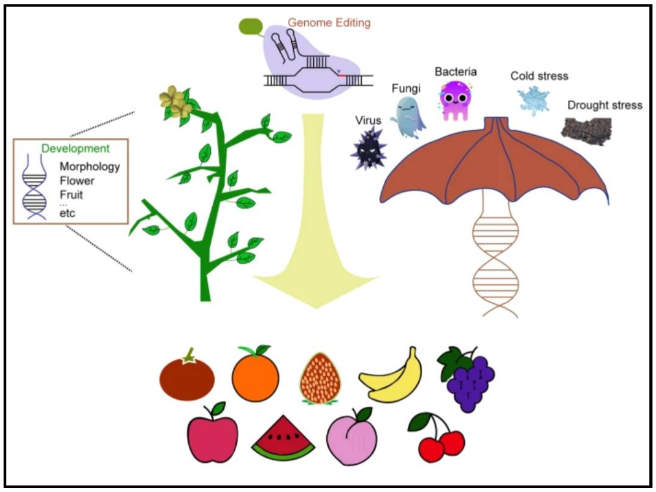

**Fig. 1:** Genome Editing for Improving Fruit Crop Development and Stress Tolerance (Source- Ma *et al*., 2023).

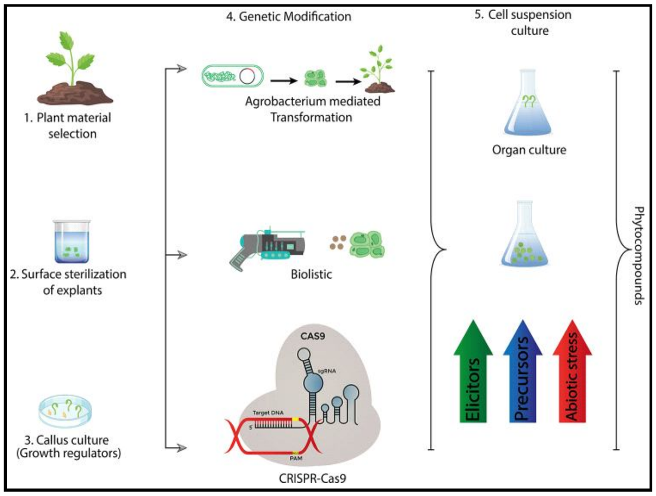

**Fig. 2:** Plant Tissue Culture and Genetic Transformation Pathways for Trait Improvement (Source- Hasnain *et al*., 2022).

- Increasingly, SNP arrays and reduced representation sequencing are being used to generate more informative marker sets for horticultural species.

### Transgenic Approaches

- The transgenic or GM approach is the introduction of DNA carrying one or more foreign gene(s) (transgenes) into a plant genome (via, e.g., Agrobacterium, biolistics) resulting in altered phenotype such as acquisition of new or enhanced traits (such as insect resistance, virus resistance, delayed ripening, improved shelf life) (Singh *et al.*, 2017).
- These strategies have been successfully employed in horticulture, although with regulatory/acceptance challenges.

### Advantages

- Allows for the introgression of traits that may not be present in cross compatible germplasm (such as insect/viro resistance genes from other species) (Talakayala *et al.*, 2020).
- Can provide new traits (such as enhanced nutrition or shelf life after harvest) more directly than relying on natural variation.

### Limitations/Challenges

- Decades may be needed for approval processes to be completed, which are expensive and inconsistent internationally, and in some cases, consumers may be reluctant to accept the products (particularly in the fresh fruit/vegetable sector) (Fernandez Rios *et al.*, 2025).
- Possible concerns: stability of the transgene, regulation of gene expression, unintended effects (Ryffel *et al.*, 2014).
- For vegetatively propagated woody crops (fruit trees), generation time is long and transformation/regeneration is hard (Yu *et al.*, 2021).

### Applications in horticulture

- Examples include virus-resistant papaya, shelf life tomato, etc (however, adoption is not uniform globally) (Yuan *et al.*, 2024).
- Transgenic methods are still important for traits that are hard to obtain through conventional breeding (such as novel metabolic pathways or delayed ripening).

### Genome Editing (CRISPR/Cas, TALENs, ZFNs)

- Genome editing tools, including CRISPR/Cas, TALENs and ZFNs, allow precise targeted alteration of the plant genome, such as gene knock out, allelic substitutions, base editing and transcriptional modulation.
- For instance, CRISPR/Cas9 involves a guide RNA that targets the Cas9 nuclease to a particular DNA sequence, which leads to a double strand break that is repaired (frequently through non homologous end joining) resulting in a mutation (Gan and Ling, 2022).

### Advantages

- High accuracy and speed in comparison to classical transgenics or traditional breeding. It enables multiplex gene editing (several targets at the same time) (Rukavtsova *et al.*, 2022).
- Could be promising for trait enhancement in horticultural crops (disease/abiotic stress tolerance, fruit quality and architecture) (Devi *et al.*, 2022).
- In case of fruit/vegetable crops with long generation intervals, genome editing offers the prospect of accelerated development of the better material.

### Limitations/Challenges

- The delivery of editing reagents (in particular for woody and recalcitrant species) and plant regeneration represent bottlenecks in many horticultural species (Ma *et al.*, 2023).

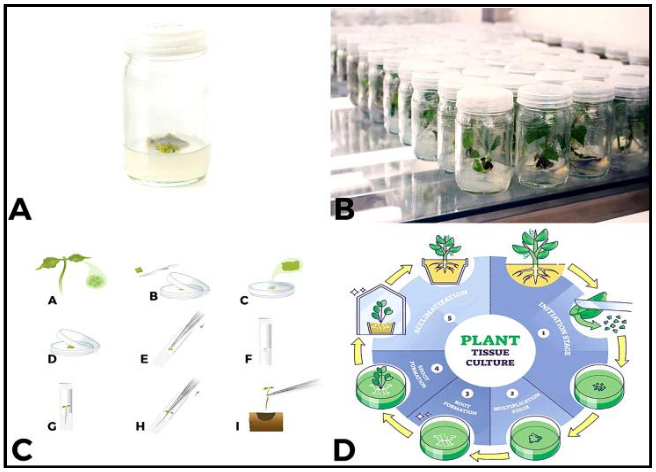

**Fig. 3:** An overview of tissue culture process **(A, B)** small explant develops callus which then produces shoots a few weeks after being placed into tissue culture media **(C)** "A to I" shows complete procedure from single cell placement to MS media to development of a complete plant **(D)** How all phases in plant tissue culture from initiation, multiplication, root formation, shoot formation and acclimatization occurs (Source-Hasnain *et al.*, 2022).

- Off target edits, regulatory uncertainty, public acceptance concerns and so forth remain (Daniel *et al*., 2023).
- It can be more complicated to obtain homozygous edits in vegetatively-propagated or heterozygous crops, too.

**Applications in horticulture**

- Fruit crops: various recent reviews cover CRISPR in fruit crops for ripening, development, and disease resistance (Ma *et al*., 2023).
- Vegetables: there is a review on genome editing in improvement of vegetable crops (Devi *et al*., 2022).
- Ex: Multiplex CRISPR/Cas9 editing of different fruit colours (knock-out of PSY1, MYB12, SGR1) in tomato in less than a year (Yang *et al*., 2023).

### Tissue Culture, Micropropagation and Somatic Embryogenesis

- Tissue culture is the culturing of cells, tissues or organs of a plant in a test tube under aseptic conditions on a defined culture medium supplemented with plant growth regulators to regenerate new plant(s) (through organogenesis or somatic embryogenesis).
- Micropropagation is the rapid clonal propagation of superior plants, generally virus-free, by means of tissue culture.
- Somatic embryogenesis, i.e. the formation of embryos from somatic (non-gamete) cells, allows production of synthetic seeds, cryopreservation, etc (Micheli and Standardi, 2016).

**Advantages**

- Facilitates speedy propagation of high-quality or disease-free planting material (particularly for vegetatively propagated crops, ornamentals) (Sharma and Kathayat, 2021).
- Required as regeneration/regrowth phase for transformation or genome-editing pipelines.
- Storage of germplasm (cryopreservation, slow-growth storage) also available.

**Limitations/Challenges**

- Some species refuse to be regenerated or to undergo somatic embryogenesis; the protocols may require an adjustment on a speciesspecific basis (Sota *et al*., 2025).
- Micropropagation can be labor-intensive, expensive, and scale-up could be difficult (Sharma and Kathayat, 2021).
- Somaclonal variation (genetic/epigenetic variation in tissue cultured plants) may reduce uniformity (81 Manchanda *et al*., 2018).

**Applications in horticulture**

- Protocols of micropropagation for banana, ornamentals and many other crops are available (Kumar *et al*., 2023).
- Tissue culture is used in the transformation/ regeneration process for most woody fruit species.
- Synthetic seed, virus-indexing (meristem culture) for disease free planting material (Naik and Buckseth, 2018).

### Omics and Phenomics Integration

- Omics: High-throughput omics methods (whole genome sequencing for genomics, RNA-seq for transcriptomics, proteomics, metabolomics, epigenomics) result in large datasets utilised to pinpoint candidate genes or biomarkers for traits of interest (Srivastava *et al*., 2024).
- Phenomics: High-throughput phenotyping on a large scale (e.g., imaging, sensors, UAVs, remote sensing) to obtain trait data (morphology, physiology, biochemistry) in a rapid and non-destructive manner (Zhao *et al*., 2019).
- The integration of multi-omics + phenomics allows a “genotype → phenotype” perspective and facilitates data-driven breeding/selection (including GS) (Cembrowska-Lech *et al*., 2023).

**Advantages**

- Facilitates the identification of candidate genes/ markers for traits and provides the dissection of complex traits (quality and stress response) through the integration of different layers of the biological system.

**Fig. 4:** *In vitro* plant propagation of plants at Tissue Culture Lab (A, B) Roots are fully developed prior to moving plants to pots of soil (Source- Hasnain *et al*., 2022).

**Table 1:** Marker and Genomic Methods: Uses and advantages.

| Method | Primary use | Advantages | Limitations |
|---|---|---|---|
| SSR, SNP genotyping | Mapping, MAS | Co-dominant, reproducible (SNPs scalable) | Need marker-trait associations |
| GWAS | Trait dissection | High resolution; uses diversity panels | Confounding population structure |
| Genomic Selection | Predict breeding values | Handles polygenic traits; reduces cycles | Requires large training sets;<br>G×E issues |

- High throughput phenotyping facilitate a faster screening of large populations enhancing selection efficacy (Rebetzke *et al.*, 2019; Yang *et al.*, 2020).
- Integratively, the omics + data analytics/AI can speed up the breeding of better cultivars (Liang *et al.*, 2025; Bisht *et al.*, 2025).

### Limitations/Challenges

- Storage, analysis, and interpretation of the large data volumes is non-trivial. Demands for bioinformatics, statistical and ML/AI skills (Kumar *et al.*, 2025; Rico-Chavez *et al.*, 2022).
- Standardisation of phenotyping protocols, sensor calibration and environmental control still pose a problem.
- Integration of multiple data sets (genotype, phenotype, environment) also in its infancy in many horticultural crops.

### Applications in horticulture

- Multi-omics + AI framework for horticultural phenotyping research (Cembrowska-Lech *et al.*, 2023).
- Genomics + transcriptomics applications in horticultural crops for trait discovery (Bashir *et al.*, 2023; Ghag *et al.*, 2022).

## Recent Advances and Applications- Detailed Sections

### Marker Technologies and Genomic Selection

- **SNP discovery and genotyping arrays:** Decreasing costs in sequencing and SNP genotyping have made high density marker maps available in tomato, apple, grape, and many other species. They enable simulation of linkage mapping, GWAS and GS model training (Tiwari *et al.*, 2022; Nybom and Lacis, 2021).
- **Applications of genomic selection:** GS can be used to predict complex traits (yield, disease resistance, fruit quality) at an earlier stage and across environments; preliminary GS program for fruit crops (i.e., apple, peach) also suggests prediction ability for polygenic traits and potential to shorten the breeding cycle time (Montesinos-López *et al.*, 2021; Liu *et al.*, 2024).

### Genome Editing- CRISPR/Cas and Beyond

- **Advances in the CRISPR/Cas system:** new Cas: evolved Cas (Cas12a, Cas12b), base editors, prime editors, and refined guide design have increased editing specificity and target range (Ma *et al.*, 2023; Anzalone *et al.*, 2020). This allowed for base substitutions without double-strand breaks and for multiplex editing of complex traits.
- **Crop-specific examples & results:** Research papers and reviews report target gene editing for ripening, sugar accumulation, disease susceptibility and response to abiotic stress in tomato, banana, grape, citrus among others; some edits provide superior traits without foreign DNA insertion, facilitating regulatory trajectory in certain jurisdictions (Sardar, 2023; Wan *et al.*, 2021).

### Tissue Culture & Micropropagation- enabling technologies

- **Disease-free propagation:** Meristem culture, thermotherapy and chemotherapy in combination with indexing provide disease-free planting material for banana, potato, strawberry and ornamentals (Ahluwalia *et al.*, 2016; Doud *et al.*, 2014).
- **Regeneration systems:** Recent advances in regeneration systems (organogenesis, somatic embryogenesis) for recalcitrant woody species have made transformation and editing possible

**Table 2:** Tissue culture methods and horticultural targets.

| Method | Typical crops | Purpose |
|---|---|---|
| Meristem culture | Banana, potato, strawberry | Virus-free propagation |
| Somatic embryogenesis | Citrus, apple, ornamentals | Mass clonal propagation, synthetic seed |
| Cryopreservation | Germplasm banks | Long-term conservation |

**Table 3:** Example trait developments using biotech in horticultural crops.

| Crop | Trait targeted | Technology used | Status (lab/field/commercial) |
|---|---|---|---|
| Tomato | Sugar & flavor | CRISPR/Cas edits | Advanced greenhouse/field testing (Wang *et al*., 2023) |
| Banana | Non-browning | CRISPR edits | Field trials / advanced testing (Tripathi *et al*., 2024) |
| Apple | Fire blight resistance | Transgenic / MAS | Field trials / limited cultivar releases (Flachowsky *et al*., 2011) |
| Strawberry | Virus-free propagation | Tissue culture + indexing | Commercial seedling production (Sharma *et al*., 2018) |

for several fruit trees (Gupta *et al*., 2020). Cryopreservation enables long-term storage for the sclereids genotypes (Muthoni *et al*., 2019; Jain *et al*., 2023).

### Omics, Systems Biology & High-throughput Phenotyping

- **Candidate gene identification:** Whole-genome scaffolding and pan-genome assembly (tomato, apple, grapevine) identified structural variants and domestication loci associated with quality and stress traits (Li *et al*., 2023; Cochetel *et al*., 2023).
- **Transcriptomics and metabolomics:** associate gene expression with pathways of flavor/aroma, pigment biosynthesis, and nutraceutical levels; can be applied to gene-specific editing or markers development (Li *et al*., 2019; Li *et al*., 2022).
- **Phenomics:** High-throughput imaging-based phenotyping along with hyperspectral sensors and machine learning facilitate objective and time-resolved trait evaluation in greenhouse and field conditions, leading to enhanced selection efficiency (Zhang *et al*., 2024; Zhang *et al*., 2023).

### Nanobiotechnology and Novel Delivery Methods

- Approaches such as nanoparticle carriers and RNP (ribonucleoprotein) delivery reduce dependence on DNA constructs and may enable transient editing or delivery to hard-to-reach tissues; these approaches are considered to have potential for eliminating regulatory issues associated with transgenics and for species that are recalcitrant to transformation (Wei *et al*., 2020; Bykonya *et al*., 2023). Although they are still developing, they are being applied or considered for application in horticulture.

### Selected Case Studies

Sweetening the tomato flavor by gene editing. Gene edits were identified that enhance sugar accumulation while still maintaining size; represents a trait-quality trade-off example being advanced for field testing.

1. Postharvest modifications for non-browning banana and more- Edits in the genes for polyphenol oxidase and associated pathways lessen browning and postharvest wastage. Several projects have announced field trial or advanced greenhouse testing (Rasane *et al*., 2024; Tripathi *et al*., 2024).
2. CRISPR edits in fruit trees (apple, grape) for disease resistance and altering pigments; obstacles are regeneration and long juvenile phases, but some success is shown with species-specific protocols (Martín-Valmaseda *et al*., 2023; Osakabe *et al*., 2018).

### Challenges and Technical Bottlenecks

- **Transformation & regeneration:** Most wood fruit species and recalcitrant crops do not have efficient regeneration protocols, which affects the rate of success for transformation and genome editing. Optimization of tissue culture remains a prerequisite (Maharjan *et al*., 2025; Bennur *et al*., 2025).
- **Editing efficiency and off-target effects:** High-fidelity systems and novel Cas variants reduce off-target edits; however, strategies for delivery and screening need to be tailored to each crop (Ma *et al*., 2023; Cardi *et al*., 2023).
- **G × E interactions and prediction models:** For GS and phenotypic prediction, the genotype environment interactions hinder the extension of prediction models to target areas (Crossa *et al*., 2022).
- **Regulatory & IP landscape:** Depends on the region; gene edited crops that do not contain foreign DNA may be exempted from GMO regulation in some countries while they are regulated in others. Policy changes (regulatory, patent debates) affect timelines to commercialization. Recent news and policy debates There has been rapid change in 2023-2025 in several jurisdictions.

## Regulatory, Socio-Economic and Ethical Considerations

The regulation of gene-edited and transgenic horticultural crops varies greatly between countries: e.g. some are introducing product-based exemptions for certain gene edits (non-transgenic) whilst others are retaining a process-based regulatory system. Consumer acceptance, labelling, intellectual property and sharing of benefits with smallholder producers are key socio-economic issues. Transparent communication of the technology and engagement with stakeholders are important for its adoption. Recent policy discussions in Europe, Australia and other regions highlight evolving trends that scholars must track (Clark and Hobbs, 2024; Sprink *et al*., 2020).

### Future Prospects and Research Priorities

1. Enhancing regeneration/delivery systems of stubborn horticultural species (new types of explants, morphogenic regulators, nanoparticle/RNP delivery).
2. Integration of Multi-Omics with Phenomics: Towards Robust Trait Models and Markers for RQC (Cao *et al*., 2024).
3. Stacking minor alleles through multiplex editing for polygenic stress tolerance and quality traits.
4. Breeder-friendly tools & pre-breeding resources: Pre-validated markers, SNP chips and training populations that facilitate greater uptake of GS and MAS.
5. Regulatory science and socio-economics studies: Provide evidence of safety, value, and delivery pathways for edited horticultural crops.
6. Scalable micropropagation and mechanization for fast access of elite genotypes.

## Conclusion

Biotechnology is now the corner stone of modern horticulture crop enhancement, successfully supplementing and speeding the traditional breeding methods. Application of molecular markers, genomics selection, tissue culture methods, and genome editing technology has greatly reduced the length of breeding cycles and increased the accuracy of trait modification. They are especially helpful for perennials and other vegetatively propagated horticultural crops, where conventional improvement methods are slow and limited by biological constraints. With the advancements of multi-omics technologies and high-throughput phenotyping, there have been unprecedented insights into the genetic and biochemical basis of quality, stress tolerance, and productivity, facilitating data-driven decisions in breeding programs. In addition, advances in genome editing (e.g., base editing, prime editing and DNA-free delivery systems) are opening new avenues for next-generation, consumer-friendly novel cultivars with extended shelf life, enhanced nutritional properties and improved stress tolerance.

However, great challenges remain, such as the relatively low efficiency of transformation and regeneration for many woody or recalcitrant species, the development of unified phenotyping systems, and the complexity in data management and analysis. Regulatory variation, as well as consumer perception, continues to impact the speed at which biotech-derived horticultural products are adopted and commercialized. In the future, coordinated policies, better public communication, open-ended innovation and enhanced research-investment mechanisms will be essential in order to realize the full potential of biotechnology in horticulture. As technology continues to advance, biotechnology will become increasingly important in developing sustainable, climate-resilient, and high-quality horticultural production systems for generations to come.

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