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Post-Harvest Tomato Diseases and Their Management using Conventional and Advanced Biotechnological and Digital Tools

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Abstract

Post-harvest diseases in tomato cause significant losses as fungi and bacteria infect fruits through wounds, bruising, and unsuitable storage conditions. Major pathogens include *Alternaria*, *Colletotrichum*, *Botrytis*, *Rhizopus*, and soft-rot bacteria. Traditional practices such as careful handling, sanitation, proper grading, clean packaging, and cold storage reduce decay but provide inconsistent protection. Treatments like hot-water dips, edible coatings, and biocontrol agents offer additional benefits yet remain insufficient. Recent advances in biotechnology and digital tools such as genetic engineering, CRISPR/Cas editing, whole-genome sequencing, hyperspectral imaging, and multi-omics enable early detection, precise pathogen identification, and durable resistance, offering a comprehensive framework to minimize tomato post-harvest losses.

1. Introduction

Tomato (*Solanum lycopersicum*) is one of the most widely consumed vegetable crops botanically a fruit and forms an essential component of daily diets in salads, curries, sauces, chutneys, and numerous culinary preparations (Taha et al., 2023). However, its high perishability makes it highly vulnerable to post-harvest deterioration. Farmers, traders, and consumers frequently face severe losses due to rapid fruit rots, which can destroy marketable produce within a few days (Biradar et al., 2021a, 2021b; Devappa et al., 2021). In several developing regions, post-harvest losses may reach 20–40%, making spoilage a major yet often underrecognized constraint in the tomato supply chain (Biradar et al., 2021c; Sunkad and Kasi Rao, 2022). Key pathogens such as *Botrytis cinerea*, *Alternaria alternata*, *Fusarium* spp., *Rhizopus* spp., and *Colletotrichum* spp. substantially reduce shelf life and marketable yield. Traditional management strategies remain limited due to fungicide resistance, poor early detection, and insufficient long-term host resistance. Emerging biotechnological tools genome editing, omics-based breeding, hyperspectral imaging, and genomic diagnostics offer promising avenues for more effective and sustainable post-harvest disease management.

2. Factors affecting post-harvest decay in tomato fruits:

High moisture content: Ripe tomatoes are about 94–95% water. Microbes thrive in moist, nutrient-rich tissues, making tomatoes an ideal host.

Soft texture at ripening: As tomatoes ripen, enzymes break down the cell walls to develop soft, juicy flesh. This same softness allows pathogens to invade more easily.

Delicate skin: Even minor scratches, insect punctures, or harvesting injuries can serve as entry points for fungi and bacteria.

Climacteric fruit behavior: Tomatoes continue to ripen after harvest, producing ethylene. This accelerates senescence, making tissues more susceptible to decay organisms.

Krishi Netra
ISSN : 3048-5207

3. Major Post-Harvest Rot Pathogens

1. Alternaria rot (*Alternaria alternata*)

This fungus causes black, sunken lesions on the fruit surface, often starting at cracks or stem scars. Alternaria rot spreads rapidly during transportation and storage, especially when fruits are overripe or bruised (Biradar et al., 2021a; 2021b; 2021c).

2. Anthracnose (*Colletotrichum* spp.)

Often appearing as small, circular sunken spots, anthracnose is notorious in tropical regions. While symptoms may remain hidden at harvest, they expand quickly during storage (Biradar et al., 2021a; 2021b).

3. Rhizopus soft rot (*Rhizopus stolonifer*)

Commonly known as bread mold, Rhizopus causes a soft, watery rot. Infected fruits may collapse into a watery mass with cottony fungal growth. This pathogen spreads quickly through handling and contact with other fruits.

4. Botrytis rot (*Botrytis cinerea*)

Also called gray mold, it causes soft, brown areas covered with fuzzy gray spores. Botrytis thrives in cool but humid storerooms and can spread through the air.

5. Bacterial soft rot (*Pectobacterium* and *Pseudomonas* spp.)

Bacterial rots produce a pungent smell and watery breakdown of tissues. Once bacteria enter through wounds, they multiply rapidly and can spoil entire batches.

6. Others

- Harvest injuries: Rough picking, nail scratches, or dropping fruits create microscopic breaks.
- Poor field sanitation: Tomatoes infected with early blight, fruit borer damage, or blossom-end rot are more vulnerable.
- Unhygienic crates or baskets: Reusing dirty containers allows pathogens to accumulate and transfer to healthy fruits.
- High temperature and humidity: Warm conditions accelerate microbial growth and fruit respiration.
- Delayed marketing: Longer market chains worsen spoilage, especially without cooling facilities.

4. Management of post-harvest fruit rot in tomato

4.1 Conventional methods

1. Gentle Harvesting and Handling

Avoiding rough handling is one of the most effective ways to reduce rot. Workers should:

- Clip fruits instead of pulling them
- Avoid picking during or after rains when fruits are wet

Krishi Netra
ISSN : 3048-5207

- Keep fingernails short to prevent scratches
- Sort out damaged or diseased fruits immediately

2. Using Clean Containers

Plastic crates are far better than bamboo baskets or gunny bags. They prevent bruising and are easier to wash and sanitize between uses.

3. Field Hygiene

Removing diseased fruits and debris helps reduce inoculum levels. Managing fruit borer and fungal diseases in the field also minimizes post-harvest infections.

4. Sorting and Grading

Separating ripe from unripe fruits, and removing damaged ones, prevents infection from spreading. Even one rotten tomato can spoil an entire crate during transport.

5. Temperature Management

Cooling is the most powerful tool for slowing decay. Ideally, tomatoes should be stored at 12–15°C. Though cold storage facilities may be limited, simple low-cost technologies like:

- evaporative cool chambers
- shaded storage units
- night-time harvesting can extend shelf life significantly.

6. Packaging Innovations

Using breathable plastic liners, cushioning materials, or modified atmosphere packaging slows down respiration and reduces physical damage.

7. Safe Post-Harvest Treatments

Several options help suppress pathogens:

- Hot water dips
- Plant-based antimicrobial extracts and essential oils (Biradar et al., 2021a; 2021c)
- Food-grade coatings such as wax, chitosan, or aloe gel
- Biological control agents like *Trichoderma* (Biradar et al., 2021b)

4.2 Advanced methods

1. Genetic Engineering for Post-Harvest Disease Resistance

Genetic engineering enables precise modification of metabolic and structural pathways that influence susceptibility, firmness, cuticle integrity, and pathogen colonization (Biradar Pratiksha et al., 2023).

Enhancing Antifungal Defense Pathways

Krishi Netra
ISSN : 3048-5207

Transgenic overexpression of pathogenesis-related (PR) proteins, chitinases, β-1,3-glucanases, and antimicrobial peptides can strengthen fruit immunity, particularly against *Botrytis* and *Alternaria*. Engineered lines with boosted jasmonic acid (JA) and salicylic acid (SA) signaling show slower pathogen progression during storage.

Improving Fruit Firmness and Shelf Life

Fruit firmness is a critical determinant of disease entry. Genetic manipulation of Polygalacturonase (PG), Pectin methylesterase (PME) and Expansin genes helps stabilize cell walls and delay softening, reducing pathogen penetration.

Modifying Cuticle Biosynthesis

Altered expression of cutin and wax biosynthetic genes enhances cuticle thickness and hydrophobicity, creating physical barriers to pathogen invasion.

2. CRISPR/Cas Genome Editing in Post-Harvest Disease Management

CRISPR/Cas has revolutionized trait engineering due to its accuracy, efficiency, and regulatory benefits in several countries (Patait Neha et al., 2024).

Editing Susceptibility (S) Genes

Loss-of-function edits in S-genes delay pathogen colonization. For examples,

- *SlDMR6* homologs – increasing broad-spectrum fungal tolerance
- Genes regulating ethylene-mediated softening
  Such edits reduce microscopic lesions that serve as pathogen infection courts.

Modifying Ripening Regulators

Targeted edits in *RIN* (Ripening-Inhibitor) *NOR* (Non-Ripening) *ACS*/*ACO* (ethylene biosynthesis genes) can fine-tune ripening kinetics, lowering rot incidence without compromising flavor.

Multiplex Editing

CRISPR allows simultaneous editing of multiple genes influencing firmness, cuticle properties, and immunity an efficient approach for post-harvest resilience.

3. Whole-Genome Sequencing for Pathogen Detection and Tracking

Whole-genome sequencing has emerged as a critical tool for understanding pathogen populations affecting tomato during storage and transit (Biradar and Patil, 2023).

Pathogen Identification and Strain Typing

WGS accurately identifies pathogens, detects latent infections, and resolves species complexes such as *Colletotrichum gloeosporioides* species group.

Monitoring Fungicide Resistance

Genomic surveillance of pathogens reveals mutations associated with QoI resistance (*cytb* gene mutations),

Krishi Netra
ISSN : 3048-5207

MBC resistance (β-tubulin mutations), DMI fungicide resistance (CYP51 alterations). This enables evidence-based fungicide recommendations and resistance management.

Tracking Contamination Sources

High-resolution genomic fingerprints help trace pathogen movement from field to packinghouses, among cold-storage facilities, across supply-chain nodes.

4. Hyperspectral Imaging (HSI) for Early Detection of Post-Harvest Diseases

HSI integrates imaging and spectroscopy to capture subtle biochemical and structural changes in fruit tissues (Patil et al., 2023).

Pre-Symptomatic Detection

HSI can detect pathogen-induced changes before visual symptoms appear, enabling early sorting and decay prevention.

Machine Learning Integration

Machine learning models trained on spectral signatures classify healthy, infected, bruise-damaged, overripe fruit. This non-destructive, rapid screening tool is highly suitable for packing-line automation.

Quality and Physiological Assessment

HSI also estimates fruit firmness, moisture content, soluble sugars, all contributing indirectly to disease susceptibility.

5. Multi-Omics Approaches (Transcriptomics, Proteomics, Metabolomics, Microbiomics)

Omics platforms offer a systems-level understanding of tomato fruit–pathogen interactions (Biradar and Namrata, 2024; Rao and Sunkad, 2024).

Transcriptomics

RNA-seq reveals gene networks involved in defense, cuticle production, oxidative stress, ripening control. This guides gene selection for CRISPR or RNAi-based interventions.

Proteomics

Proteomic profiling identifies stress-related proteins, PR proteins, and enzymes linked to fruit deterioration and pathogen invasion.

Metabolomics

Metabolite fingerprints indicate biochemical markers of disease susceptibility such as defensive phenolics, organic acids, cell-wall–associated metabolites.

Conclusion

Tomato post-harvest rots significantly reduce market quality and cause major economic losses, largely due to fungal and bacterial pathogens that exploit wounds, poor handling, and inadequate storage. Improved harvesting, sanitation, sorting, and temperature management can substantially limit spoilage. Emerging

Krishi Netra
ISSN : 3048-5207

technologies genome editing, whole-genome sequencing, hyperspectral imaging, and multi-omics now enable early detection and resilient variety development. Integrating these innovations into the supply chain offers sustainable solutions to reduce losses and preserve fruit quality.

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