International Journal of Plant & Soil Science

Volume 38, Issue 3, Page 196-210, 2026; Article no.IJPSS.154836
ISSN: 2320-7035

Biotic Stresses in Temperate Fruit Crops: Mechanisms, Challenges and Sustainable Management Strategies

Ashaq H Pandit [a++*], Gazala Mansoor [a#*], Abdul Raouf Malik [a†*], Khalid Mushtaq Bhat [a‡], G. I. Hassan [a‡] and Rafiya Mushtaq Zargar [a#]

[a] Division of Fruit Science, Faculty of Horticulture, Sher-e- Kashmir University of Agricultural Science and Technology of Kashmir, Shalimar, Srinagar 190025, Jammu and Kashmir, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i36012

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/154836

Review Article

Received: 07/01/2026
Published: 21/03/2026

Abstract

Temperate fruit crops such as apple, pear, peach, plum, and cherry constitute an important component of global horticultural production. However, their productivity is severely constrained by a wide range of biotic stresses caused by pathogenic microorganisms, insect pests, and plant-parasitic nematodes. These biotic agents significantly reduce fruit yield, quality, and orchard longevity, resulting in substantial economic losses worldwide. Major diseases such as apple scab (*Venturia inaequalis*), fire blight (*Erwinia amylovora*), and brown rot (*Monilinia* spp.), along with insect pests such as codling moth (*Cydia pomonella*), represent major threats to temperate fruit production systems. Plants have evolved sophisticated defense mechanisms to perceive and respond to invading pathogens and pests, including structural barriers, biochemical responses,

[++] Professor and Head; [#] Ph.D. Scholar; [†] Assistant Professor; [‡] Professor;
**Corresponding author: E-mail: gxalmanzoor707@gmail.com, ashaqpandit@gmail.com, roufmalik@gmail.com;*

Cite as: *Pandit, A. H., Mansoor, G., Malik, A. R., Bhat, K. M., Hassan, G. I., & Zargar, R. M. (2026). Biotic Stresses in Temperate Fruit Crops: Mechanisms, Challenges and Sustainable Management Strategies. International Journal of Plant & Soil Science, 38(3), 196–210. https://doi.org/10.9734/ijpss/2026/v38i36012*

and molecular immune signaling pathways. Key components of plant immunity include pattern-triggered immunity (PTI) and effector-triggered immunity (ETI), which together form a multilayered defense system. Advances in plant pathology and biotechnology have led to the development of integrated management strategies aimed at mitigating biotic stress. This review provides a comprehensive overview of major biotic stresses affecting temperate fruit crops, their mechanisms of infection, and plant defense responses. The review also highlights modern approaches such as integrated pest management (IPM), biological control, host resistance breeding, RNA interference (RNAi), microbiome engineering, and genome editing technologies that offer promising solutions for sustainable fruit production.

Keywords: Biotic stress; temperate fruits; plant immunity; plant defense; integrated pest management.

1. Introduction

Temperate fruit crops such as apple, pear, peach, plum, cherry, and apricot are economically important horticultural commodities cultivated across many regions of the world. These fruits are valued for their nutritional composition, providing essential vitamins, minerals, dietary fiber, and bioactive compounds beneficial to human health (FAO, 2023, 2020 et al. 2020). However, the production of temperate fruits is frequently threatened by a wide range of biotic stresses that significantly reduce yield, fruit quality, and orchard longevity (Savary et al., 2019; Strange & Scott, 2005, Berg et al. 2021).

Biotic stress refers to damage caused by living organisms including fungi, bacteria, viruses, nematodes, insects, and mites. These organisms infect plant tissues, disrupt physiological processes, and ultimately lead to reduced productivity (Agrios, 2005; Oerke, 2006). Global crop losses due to plant pests and diseases are estimated to range between 20–40%, representing a major constraint to food security and agricultural sustainability (Savary et al., 2019; FAO, 2023, Hernández-Soto and Chacón-Cerdas 2021).

Temperate fruit crops are particularly vulnerable to biotic stresses because of their perennial nature and long orchard lifespan. Once established, pathogens can persist in orchards for many years, making management difficult. For example, apple scab, fire blight, powdery mildew, and codling moth are among the most destructive problems affecting apple orchards worldwide.

Plants have evolved sophisticated defense systems to counteract pathogen invasion. These defense responses involve structural barriers, production of antimicrobial compounds, activation of defense-related genes, and complex signaling pathways (Dangl& Jones, 2001; Dodds & Rathjen, 2010). Advances in plant molecular biology have revealed two major layers of plant immunity: pattern-triggered immunity (PTI) and effector-triggered immunity (ETI) (Jones & Dangl, 2006; Boller & Felix, 2009).

Effective management of biotic stresses requires integrated strategies combining cultural practices, resistant cultivars, biological control agents, and judicious use of pesticides (Pimentel, 2009; Bebber & Gurr, 2015). In recent years, novel approaches such as genome editing, RNA interference, and microbiome manipulation have emerged as promising tools for improving disease resistance (Gupta et al., 2022, Halder et al. 2022).

This review aims to provide a comprehensive overview of the major biotic stresses affecting temperate fruit crops, plant defense mechanisms, and current management strategies. Understanding these interactions will support the development of sustainable approaches to protect fruit production systems.

2. Biotic Stress

Biotic stress in plants arises from living organisms, including viruses, bacteria, fungi, nematodes, insects, arachnids, and weeds. These biotic agents deprive host plants of essential nutrients and resources, potentially leading to severe growth inhibition or plant mortality (Agrios, 2005; Oerke, 2006). Biotic stress can significantly impact agricultural productivity and is responsible for considerable pre- and postharvest losses in many crops worldwide (Savary et al., 2019; Strange & Scott, 2005). Although plants lack an adaptive immune system similar to that found in animals, they have evolved highly sophisticated defense mechanisms to perceive and respond to pathogen attack. These defense responses are genetically regulated and involve resistance (R) genes encoded within the plant genome, often numbering in the hundreds (Dangl & Jones, 2001;

Jones & Dangl, 2006, Yu et al. 2024). The interaction between plant resistance genes and pathogen effectors plays a crucial role in determining plant susceptibility or resistance to diseases.

Biotic stress is fundamentally different from abiotic stress, which results from non-living environmental factors such as salinity, extreme temperatures, drought, flooding, and high light intensity that adversely affect crop performance (Mittler, 2006; Atkinson & Urwin, 2012, Liu et al. 2021). While abiotic stresses disrupt plant physiological processes through environmental constraints, biotic stresses involve complex interactions between plants and invading organisms.

The type and severity of biotic stress experienced by crops are strongly influenced by climatic conditions, cropping systems, and the inherent genetic capacity of plant species or cultivars to resist particular pathogens or pests (Bebber et al., 2013; Savary et al., 2019). Environmental conditions such as temperature, humidity, and rainfall often determine pathogen survival, infection rates, and disease development in crop plants.

Biotic stresses frequently impair plant physiological processes, particularly photosynthesis. For instance, chewing insects can reduce leaf area and thus limit the photosynthetic capacity of plants, while viral infections may reduce photosynthetic efficiency by disrupting chloroplast function and altering metabolic pathways (Berger et al., 2007; Bolton, 2009, Islam et al. 2024). These physiological disruptions highlight the profound effects that biotic stressors exert on plant growth, development, and productivity.

3. Major Biotic Stresses Affecting Temperate Fruits

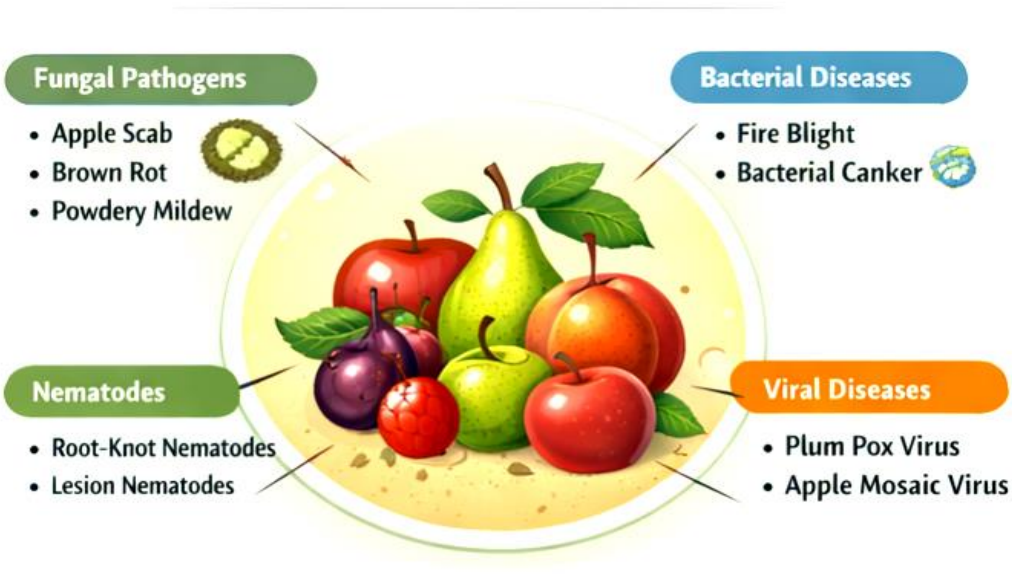

Fig. 1. Illustrates the major biotic stresses affecting temperate fruit crops

Temperate fruit crops are attacked by a diverse range of pathogens and pests that affect different plant organs including roots, leaves, flowers, and fruits. These organisms significantly reduce crop yield, fruit quality, and orchard productivity, thereby posing major challenges for sustainable fruit production (Agrios, 2005; Oerke, 2006; Savary et al., 2019, Tena 2021).

3.1 Fungal Pathogens

Fungi represent the most destructive group of pathogens in temperate fruit production and are responsible for a wide range of diseases including apple scab, powdery mildew, brown rot, leaf spots, and cankers (Agrios, 2005; Dean et al., 2012, Ali et al. 2024). These diseases can cause serious economic losses by affecting both yield and marketability of fruits.

Fungal pathogens can be broadly classified into two major categories based on their nutritional strategies:

Biotrophs – require living host tissue to survive and reproduce.
Necrotrophs – kill host tissue and feed on dead plant cells.

Biotrophic fungi establish long-term associations with host plants and often evade plant defense mechanisms, whereas necrotrophic fungi produce toxins and cell wall–degrading enzymes that rapidly destroy plant tissues (Glazebrook, 2005; Bolton, 2009).

Common fungal diseases affecting temperate fruit crops include:

- Apple scab (*Venturia inaequalis*)
- Powdery mildew (*Podosphaeraleucotricha*)
- Brown rot (*Monilinia* spp.)
- Alternaria leaf spot (*Alternaria alternata*)
- Botrytis fruit rot (*Botrytis cinerea*)

These diseases frequently result in premature defoliation, fruit blemishes, fruit rot, and ultimately significant reductions in yield and fruit quality (Dean et al., 2012).

3.2 Bacterial Diseases

Bacterial pathogens also cause severe economic losses in temperate fruit orchards. These microorganisms typically enter plant tissues through natural openings such as stomata or through wounds caused by insects, pruning, or environmental factors (Agrios, 2005).

One of the most destructive bacterial diseases in temperate fruit crops is fire blight, caused by *Erwinia amylovora,* which affects apple and pear trees worldwide. The disease spreads rapidly under warm and humid conditions and can devastate entire orchards if not properly managed (Van der Zwet et al., 2012).

Typical symptoms of fire blight include:

- Blossom blight
- Shoot wilting
- Blackened leaves and shoots
- Cankers on branches and trunks

Other important bacterial diseases affecting temperate fruits include bacterial spot caused by *Xanthomonas arboricola* and bacterial canker caused by *Pseudomonas syringae* in stone fruit crops.

3.3 Viral Diseases

Viruses are obligate intracellular parasites that depend entirely on host plant cells for replication. They are commonly transmitted by insect vectors such as aphids, mites, and leafhoppers, as well as through vegetative propagation of infected plant material (Hull, 2014).

Viral infections often result in characteristic symptoms such as:

- Mosaic patterns on leaves
- Chlorosis
- Stunted plant growth
- Reduced fruit yield and quality

Important viral diseases affecting temperate fruit crops include:

- Apple mosaic virus
- Plum pox virus (Sharka disease)
- Cherry leaf roll virus

Because viruses cannot be effectively controlled through chemical treatments, management primarily relies on preventive measures such as the use of certified virus-free planting material, vector control, and strict quarantine measures (Hull, 2014; Rimbaud *et al*., 2015, Ku et al. 2024).

3.4 Nematodes

Plant-parasitic nematodes are microscopic roundworms that inhabit the soil and feed on plant roots, thereby disrupting water and nutrient uptake (Jones et al., 2013). These pests can significantly reduce plant vigor and productivity in fruit orchards.

Among the most important nematodes affecting temperate fruit crops are root-knot nematodes (*Meloidogyne* spp.) andlesion nematodes (*Pratylenchus*spp.).

Nematode infestations typically cause:

- Root galls and deformities
- Reduced root growth
- Nutrient deficiencies
- Decline in tree vigor and productivity

Furthermore, nematode damage often predisposes plants to secondary infections by fungal and bacterial pathogens, thereby increasing disease severity (Jones et al., 2013).

3.5 Insect Pests

Insects and mites represent another major group of biotic stressors affecting temperate fruit crops. These pests cause damage through feeding activities, egg laying (oviposition), and transmission of plant pathogens.

Common insect pests found in temperate fruit orchards include:

- Codling moth (*Cydiapomonella*)
- Aphids (*Aphis* spp.)
- Leaf miners
- Fruit flies
- Spider mites

Among these, piercing–sucking insects such as aphids are particularly problematic because they not only damage plant tissues but also act as vectors for several viral and bacterial diseases (Oerke, 2006).

Climate change is expected to significantly influence the distribution, severity, and epidemiology of plant diseases and insect pests in temperate fruit production systems. Rising temperatures, altered rainfall patterns, and increased atmospheric carbon dioxide concentrations can affect pathogen survival, reproduction, and dispersal, potentially leading to the emergence of new disease outbreaks in previously unaffected regions. Changes in climate may also influence host susceptibility and pest population dynamics, thereby increasing the complexity of disease management in fruit orchards (Bebber *et al*., 2013; Garrett *et al*., 2014). Understanding the interactions among climate, host plants, and pathogens will therefore be critical for developing climate-resilient disease management strategies.

4. Plant Defense Mechanisms Against Biotic Stress

Plants possess complex and highly coordinated defense systems that enable them to detect invading pathogens and activate appropriate immune responses. These defense mechanisms involve structural barriers, biochemical compounds, and sophisticated molecular signaling pathways that help plants resist or tolerate pathogen attack (Dangl & Jones, 2001; Jones & Dangl, 2006; Dodds & Rathjen, 2010).

Table 1. Major biotic stresses affecting temperate fruit crops

Pathogen/Pest Group	Examples of Diseases/Pests	Host Crops	Major Symptoms
Fungi	Apple scab, powdery mildew, brown rot	Apple, pear, peach	Leaf spots, fruit rot
Bacteria	Fire blight, bacterial spot	Apple, pear, peach	Cankers, shoot blight
Viruses	Apple mosaic virus, plumpox virus	Apple, plum, cherry	Mosaic patterns, stunting
Nematodes	Root-knot nematodes	Various fruit crops	Root galls, poor growth
Insects	Codling moth, aphids, mites	Apple, pear, peach	Fruit damage, vector transmission

4.1 Structural Barriers

The first line of defense in plants consists of physical and structural barriers that prevent the entry and establishment of pathogens. These structures act as passive defense mechanisms that limit pathogen penetration into plant tissues (Agrios, 2005, Zhang et al. 2023).

Important structural barriers include:

- Thick cuticle
- Wax layers
- Cell walls
- Bark tissues
- Trichomes

The plant cuticle and wax layers provide a protective outer covering that restricts pathogen attachment and entry, while cell walls serve as strong mechanical barriers against microbial invasion. Trichomes and bark tissues further contribute to plant defense by reducing pathogen colonization and insect feeding (Beckman, 2000; Agrios, 2005).

4.2 Chemical Defenses

Plants also produce a wide range of antimicrobial compounds that act as chemical defenses against pathogens. Among these, phytoalexins are important secondary metabolites synthesized in response to pathogen attack and function to inhibit pathogen growth and spread (Ahuja et al., 2012).

Other important chemical defense compounds include:

- phenolic compounds
- flavonoids
- terpenoids
- alkaloids

These secondary metabolites possess antimicrobial, antioxidant, and signaling properties that contribute significantly to plant immunity and defense responses (Dixon, 2001; Ahuja et al., 2012).

4.3 Pattern-Triggered Immunity (PTI)

Plants recognize conserved molecular structures present in pathogens, known as pathogen-associated molecular patterns (PAMPs), throughpattern recognition receptors (PRRs) located on the plant cell membrane. This recognition activates a basal immune response known as pattern-triggered immunity (PTI) (Boller & Felix, 2009; Jones & Dangl, 2006).

Activation of PTI leads to several defense responses including:

- production of reactive oxygen species (ROS)
- strengthening of plant cell walls through callose deposition
- activation of defense-related genes
- synthesis of antimicrobial compounds

PTI represents the first active layer of the plant immune system and plays a critical role in restricting pathogen invasion at the early stages of infection (Boller & Felix, 2009).

4.4 Effector-Triggered Immunity (ETI)

Many pathogens secrete specialized molecules called effector proteins that suppress PTI responses and facilitate infection. In response, plants have evolved resistance (R) genes that recognize these pathogen effectors and trigger a stronger immune response known as effector-triggered immunity (ETI) (Jones & Dangl, 2006; Dodds & Rathjen, 2010).

ETI responses are generally more rapid and robust than PTI and often involve a hypersensitive response (HR), a localized form of programmed cell death at the infection site that restricts pathogen spread within plant tissues (Coll *et al*., 2011). ETI also leads to the activation of systemic defense signaling pathways that enhance resistance throughout the plant.

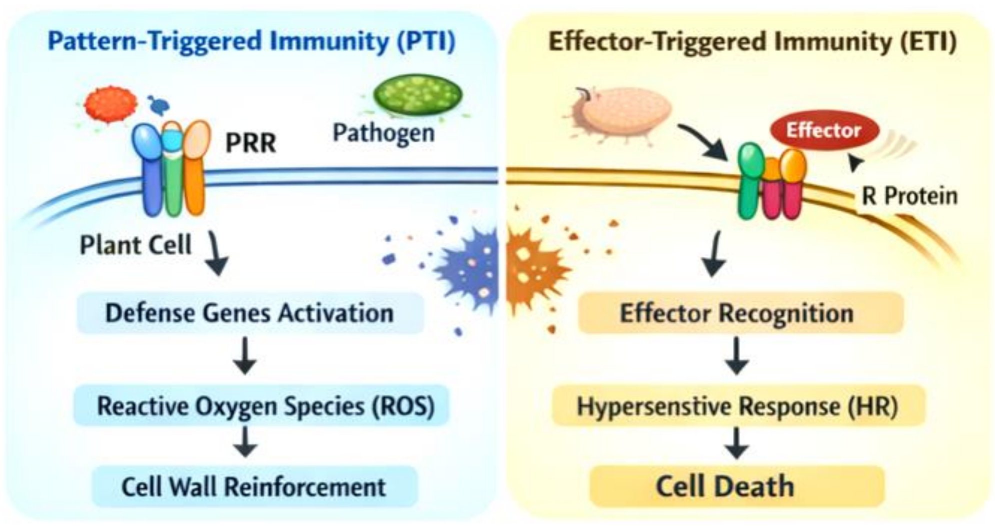

Fig. 2. Shows the two major layers of plant immune responses: PTI and ETI

4.5 Defense Signaling Hormones

Plant immune responses are tightly regulated by a complex network of signaling molecules, among which phytohormones play a central role. The most important defense-related hormones include salicylic acid (SA), jasmonic acid (JA), and ethylene (ET). These signaling molecules coordinate plant responses against different types of pathogens and pests. Salicylic acid is primarily associated with resistance against biotrophic and hemibiotrophic pathogens. It plays a key role in systemic acquired resistance (SAR), a long-lasting defense response that enhances resistance throughout the plant following localized infection. In contrast, jasmonic acid and ethylene are mainly involved in defense against necrotrophic pathogens and herbivorous insects. These hormones regulate the expression of numerous defense-related genes and the production of antimicrobial compounds. The interaction among SA, JA, and ET signaling pathways forms a complex regulatory network that enables plants to mount appropriate defense responses depending on the type of invading pathogen or pest (Pieterse *et al*., 2014; Peng *et al*., 2021).

Table 2. Major plant defense mechanisms against pathogens

Defense Type	Mechanism	Function
Structural	Cuticle, bark, trichomes	Prevent pathogen entry
Chemical	Phytoalexins, phenolics	Antimicrobial activity
PTI	Recognition of pathogen patterns	Basal immunity
ETI	R-gene mediated recognition	Strong immune response

5. Integrated Management Strategies for Biotic Stress

Effective management of biotic stresses in temperate fruit crops requires an integrated approach that combines multiple disease management strategies. Integrated disease management (IDM) involves the coordinated use of cultural, biological, genetic, and chemical methods to minimize crop losses while ensuring environmental sustainability (Agrios, 2005; Pimentel, 2009; Lamichhane et al., 2016).

Fig. 3. Presents the framework of Integrated Pest Management (IPM) strategies

5.1 Cultural Practices

Cultural practices represent the first line of defense in disease prevention and play an important role in reducing pathogen establishment and spread in orchards. These practices focus on modifying the crop environment to make it less favorable for pathogen development (Agrios, 2005).

Common cultural practices include:

- orchard sanitation
- removal and destruction of infected plant material
- proper pruning and canopy management
- crop rotation
- balanced fertilization and irrigation management

These practices help reduce pathogen inoculum levels, improve air circulation within orchards, and enhance overall plant health, thereby reducing disease incidence (Lamichhane et al., 2016).

5.2 Host Plant Resistance

The development and cultivation of disease-resistant cultivars is considered one of the most sustainable and environmentally friendly approaches for managing biotic stresses in fruit crops (Brown, 2015). Resistant varieties can significantly reduce dependence on chemical pesticides and lower production costs.

Modern breeding programs utilize advanced techniques such as:

- marker-assisted selection (MAS)
- genomic selection
- gene editing technologies (e.g., CRISPR/Cas9)

These tools facilitate the identification and incorporation of resistance genes into improved cultivars, thereby accelerating breeding programs and enhancing disease resistance in temperate fruit crops (Collard & Mackill, 2008; Chen et al., 2019).

5.3 Biological Control

Biological control involves the use of beneficial microorganisms or natural enemies to suppress plant pathogens and pests. This approach has gained increasing attention as a sustainable alternative to chemical pesticides (Poveda, 2021).

Common biological control agents include:

- *Bacillus* species
- *Trichoderma* species
- *Pseudomonas* species

These microorganisms suppress pathogens through several mechanisms, including competition for nutrients and space, production of antimicrobial compounds, parasitism, and induction of plant defense responses (Harman et al., 2004; Poveda, 2021).

5.4 Chemical Control

Chemical pesticides remain an important tool for managing severe disease outbreaks in temperate fruit orchards. Fungicides, bactericides, and insecticides are widely used to control pathogens and insect pests that threaten fruit production (Oerke, 2006).

However, excessive or improper use of chemical pesticides can lead to several problems, including environmental contamination, pesticide residues in food products, and the development of pesticide-resistant pathogen populations (Pimentel, 2009; Lamichhane et al., 2016). Therefore, chemical control should be applied judiciously and integrated with other management strategies within an Integrated Pest Management (IPM) framework.

Table 3. Integrated strategies for managing biotic stress in temperate fruits

Strategy	Examples	Benefits
Cultural practices	Sanitation, pruning	Reduces pathogen load
Resistant cultivars	Disease-resistant varieties	Long-term control
Biological control	Beneficial microbes	Environmentally safe
Chemical control	Fungicides, insecticides	Rapid disease suppression

6. Emerging Technologies for Biotic Stress Management

Recent advances in plant science and biotechnology have provided innovative tools for managing biotic stresses in crop plants. These technologies enhance our understanding of plant–pathogen interactions and offer new strategies for developing disease-resistant crops and sustainable plant protection systems (Gupta et al., 2022).

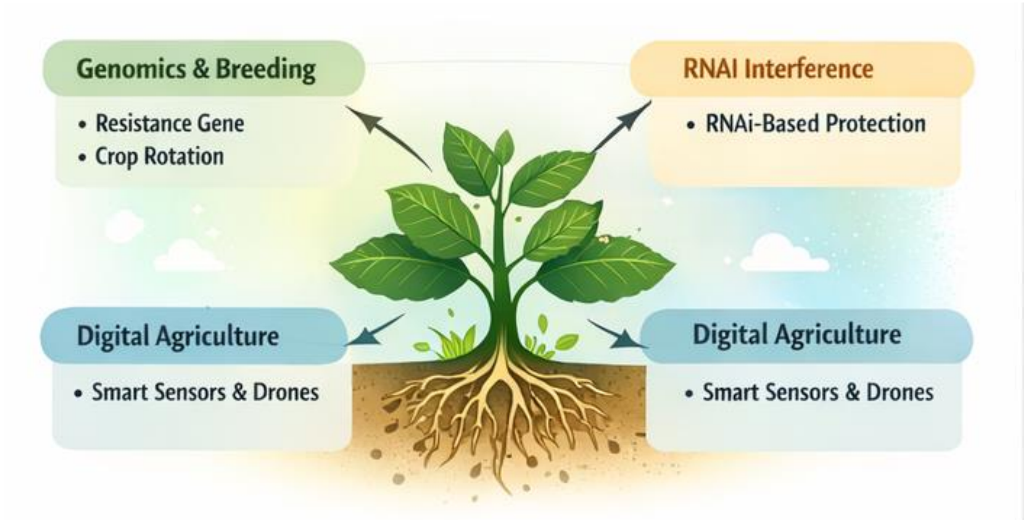

Fig. 4. Highlights emerging technologies for disease management

6.1 Genomic Approaches

Advances in genomics, transcriptomics, and other “omics” technologies have significantly improved our understanding of the molecular mechanisms underlying plant–pathogen interactions. These tools enable the identification of resistance (R) genes, defensesignaling pathways, and host responses to pathogen attack (Dodds & Rathjen, 2010, Jones et al. 2020).

Genomic approaches such as whole-genome sequencing, genome-wide association studies (GWAS), andtranscriptome analysis allow researchers to identify genes involved in disease resistance and stress tolerance. These discoveries provide valuable resources for crop improvement programs and facilitate the development of disease-resistant fruit cultivars through molecular breeding strategies (Varshney et al., 2021).

6.2 RNA-Based Plant Protection

RNA interference (RNAi) technology has emerged as a promising strategy for plant disease management. RNAi works by silencing specific genes involved in pathogen infection and virulence, thereby preventing disease development (Koch & Kogel, 2014). In RNA-based plant protection, small interfering RNAs (siRNAs) or double-stranded RNAs (dsRNAs) are used to target and suppress essential genes in pathogens or insect pests. This approach offers highly specific and environmentally friendly disease control with minimal impact on non-target organisms (Wang & Jin, 2017).

RNAi-based technologies are increasingly being explored for controlling fungal pathogens, viruses, and insect pests in several agricultural crops.

6.3 Microbiome Engineering

Plant-associated microbial communities, collectively known as the plant microbiome, play a crucial role in plant health and disease resistance. Beneficial microorganisms present in the rhizosphere, phyllosphere, and endosphere can enhance plant growth and protect plants from pathogens (Berg et al., 2020).

Recent research has focused on microbiome engineering, which involves manipulating microbial communities to improve plant resilience against biotic stresses. Beneficial microbes such as *Bacillus*, *Pseudomonas*, and *Trichoderma* species can suppress pathogens through mechanisms such as competition, antibiosis, and induction of systemic resistance (Pieterse et al., 2014; Berg et al., 2020).

Harnessing plant microbiomes offers a promising and sustainable approach to disease management and has the potential to reduce reliance on chemical pesticides in agricultural systems.

Table 4. Emerging technologies for managing plant diseases

Technology	Application	Advantages
Genome editing	CRISPR-based resistance	Precise gene modification
RNA interference	Pathogen gene silencing	Target-specific control
Microbiome engineering	Beneficial microbial communities	Improved plant immunity

7. Future Research Directions

Recent advances in digital agriculture, including remote sensing, drone-based monitoring, machine learning, and artificial intelligence, are providing new opportunities for early disease detection and precision crop protection. These technologies enable rapid identification of disease symptoms, monitoring of pathogen spread, and optimized application of control measures. Integration of digital tools with conventional plant pathology approaches may significantly improve disease surveillance and management efficiency in temperate fruit production systems.Despite considerable advances in plant pathology, biotechnology, and integrated pest management strategies, several challenges remain in effectively managing biotic stresses in temperate fruit crops. The increasing prevalence of emerging pathogens, the evolution of pesticide resistance, and the impacts of climate change on host–pathogen interactions necessitate the development of innovative and sustainable management strategies (Bebber et al., 2013; Savary et al., 2019). One important area of future research is the identification and characterization of new resistance genes in temperate fruit crops. Advances in genomics, transcriptomics, and genome-wide association studies (GWAS) provide powerful tools for discovering novel resistance loci and understanding their functional roles in plant defense. The integration of molecular breeding techniques such as marker-assisted selection and genome editing technologies, including CRISPR/Cas systems, has the potential to accelerate the development of disease-resistant cultivars (Varshney et al., 2021; Chen et al., 2019).

Another critical research priority involves the development of rapid and accurate diseasedetection systems. Early detection of plant pathogens is essential for timely disease management and prevention of large-scale outbreaks. Recent progress in molecular diagnostics, biosensors, remote sensing, and artificial intelligence-based disease detection systems offers promising opportunities for monitoring plant health and identifying infections at early stages (Mahlein, 2016; Fang & Ramasamy, 2015, Busby et al. 2021).

The integration of biological control agents with conventional management practices also represents an important research direction for sustainable agriculture. Beneficial microorganisms such as *Trichoderma*, *Bacillus*, and *Pseudomonas* species have shown considerable potential in suppressing plant pathogens and enhancing plant immunity. Future research should focus on improving the stability, formulation, and field performance of these biological agents, as well as understanding their interactions with plant hosts and soil microbial communities (Poveda, 2021; Pieterse et al., 2014). Climate change is expected to significantly alter the distribution, survival, and virulence of plant pathogens and insect pests. Rising temperatures, changes in rainfall patterns, and increased atmospheric carbon dioxide levels may influence host–pathogen interactions and disease epidemiology in temperate fruit production systems (Bebber et al., 2013; Garrett et al., 2014). Therefore, future studies should focus on understanding the impacts of climate change on pathogen dynamics and developing climate-resilient disease management strategies.

Furthermore, the development of sustainable and environmentally friendly pest management systems remains a key priority for modern agriculture. Integrated pest management (IPM) strategies that combine cultural practices, resistant cultivars, biological control, and precision agriculture technologies offer promising approaches for reducing pesticide reliance while maintaining crop productivity (Lamichhane et al., 2016). Advances in molecular biology, biotechnology, digital agriculture, and microbiome research will play a crucial role in improving disease management strategies and ensuring the long-term sustainability of temperate fruit production systems.

8. Conclusion

Biotic stresses remain one of the most significant challenges to temperate fruit production worldwide. A wide range of pathogens and pests, including fungi, bacteria, viruses, nematodes, and insect pests, adversely affect fruit crops by reducing yield, deteriorating fruit quality, and compromising orchard productivity. These biotic agents disrupt essential physiological and metabolic processes in plants, ultimately leading to considerable economic losses in commercial fruit production systems. Plants have evolved highly sophisticated defense mechanisms to counteract pathogen invasion. These defense strategies include structural barriers that prevent pathogen entry, the production of antimicrobial secondary metabolites, and the activation of complex molecular signalling pathways involved in plant immunity. The coordinated functioning of defense mechanisms such as pattern-triggered immunity (PTI) and effector-triggered immunity (ETI) enables plants to recognize pathogens and mount effective responses against infection.

Effective management of biotic stresses in temperate fruit crops requires a comprehensive and integrated approach that combines cultural practices, host plant resistance, biological control strategies, and judicious use of chemical pesticides. In recent years, rapid advances in plant genomics, RNA-based technologies, genome editing, and microbiome research have opened new avenues for developing sustainable and environmentally friendly plant disease management strategies.

Future efforts should focus on strengthening research on plant–pathogen interactions, improving early disease detection systems, and integrating modern biotechnological tools with conventional crop protection strategies. Such multidisciplinary approaches will be essential for enhancing resilience in temperate fruit production systems and ensuring sustainable horticultural productivity under changing environmental conditions. The integration of advanced biotechnological tools, ecological management strategies, and digital agriculture technologies will play a crucial role in developing resilient and sustainable fruit production systems in the future.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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