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DETECTION AND PREVENTION OF FUNGAL PATHOGENS IN HORTICULTURAL AND KIWIFRUIT PRODUCTS: A COMPREHENSIVE REVIEW

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ABSTRACT

Fruit, flower, and horticultural vegetables are under attack by fungal pathogens, which infect postharvest fruits in general, including kiwifruit. The impact of such pathogens leads to economic losses, reduced fruit quality, and market problems. The pathogens not only lead to postharvest losses but also disrupt food safety by producing toxic mycotoxins. This comprehensive review accounts for for fungal diseases in many horticultural plants, critical fungal diseases of fruit and vegetable plants, and their corresponding symptoms, e.g., the primary fungal diseases of kiwifruit, and discusses conventional, molecular, and emerging non-destructive methods for fungal pathogen detection and prevention. The traditional detection devices, such as visual inspection with the eye and cultivation, are time-bound and vulnerable. Besides, the application and use of current molecular technologies, such as PCR, qPCR, and LAMP, now enable specific identification. Nowadays, non-destructive disease detection techniques such as electronic noses and hyperspectral imaging enable early detection of various diseases without destroying the produce. This review also recommends several prevention strategies, including chemical control with various fungicides, cultural practices, and biological control using multiple approaches, such as beneficial microbes, essential oils, plant natural products, and nanotechnology-based strategies. Recently, emerging disciplines such as genome editing, precision horticulture, and microbiome sequencing are pillars of future advances in the prevention and early detection of plant fungal diseases.

Keywords: Fungal Pathogens, Postharvest Diseases, Detection Methods, Prevention Strategies, Kiwifruit, Horticulture.

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1. INTRODUCTION

The various horticultural crops, including fruits, vegetables, and flowers, are the backbone of agriculture, providing food, nutritional security, rural incomes, and economic stability. Among these, fruits are most valued for their substantial market and nutritional value. As they are delicate by nature, they are susceptible to postharvest deterioration, especially under warm, humid storage conditions. Of the postharvest diseases, blue mold (*Penicillium expansum*), gray mold (*Botrytis cinerea*), and black rot (*Guignardia bidwellii*) are long-standing problems in fruits. They reduce market quality and, in some cases, introduce mycotoxins that compromise food safety (Udriste et al. 2018; Xu et al. 2022; Liu et al. 2024a). Vegetable crops, while less prominent than fruit crops in export economies, are also prone to fungal infection, reducing yield and quality. Pathogens such as *Alternaria solani* (early blight), *Phytophthora infestans* (late blight), and *Bremia lactucae* (Downy mildew) infect vegetable crops such as tomatoes, potatoes, and cucurbits (Romero-Cuadrado et al. 2024). Fungal pathogens prefer high humidity and cause the same postharvest issues. Of horticulturally important crops, kiwifruit (*Actinidia* spp.) is economically important as well as nutritionally important. It is indigenous to China and commercially produced in New Zealand, Italy, and China and is highly valued for its unique flavor and nutritional value (Dai et al. 2022; Park et al. 2023; Rai et al. 2025a). New Zealand, for example, kiwifruit is the nation's second-largest exporting horticultural crop, worth over NZ$2 billion annually. It sustains thousands of farmers by virtue of its spillover connections with logistics, research, and processing sectors (Scrimgeour et al. 2017). Also, environmentally friendly kiwifruit production measures have helped preserve the environment without compromising on productivity (Müller et al. 2015). The sector has also served as an example of adaptability with the production of tolerant varieties and cultural whole-program measures in anticipation of future stress (Wu 2020).

The kiwifruit cultivation practices would be vulnerable to a wide range of pre- and postharvest fungal diseases. The old offenders such as *Botrytis cinerea* and *Penicillium spp*., are faced with the new-type challenges, such as *Didymella glomerata*, the causative agent of the black spot disease, and *Verticillium nonalfalfae*, a soilborne pathogen of pandemic outbreak potential (Dai et al. 2022; Wang et al. 2022a; Park et al. 2023; Haghbin et al. 2023).

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These fungal pathogens have a dual harmful impact by decreasing the quality of the fruit and affecting international trade, for which effective action is required. Some non-chemical control means, including temperature control and gamma irradiation, have been found effective in reducing fungal load without compromising fruit integrity (Yaşa et al. 2018). These are of particular utility during postharvest handling and transportation, where microbial safety is of utmost importance.

Horticultural produce maintains a history of high productivity for all types of crops but is not free from postharvest loss. Fig. 1 indicates the average per-hectare yield of six high-value fruits: Apples, Oranges, Bananas, Watermelons, Tomatoes, and Kiwifruit with variation caused by cultural practice, environmental effect, and diseases that occur (Pesteanu and Gudumac 2008; Zamora et al. 2010).

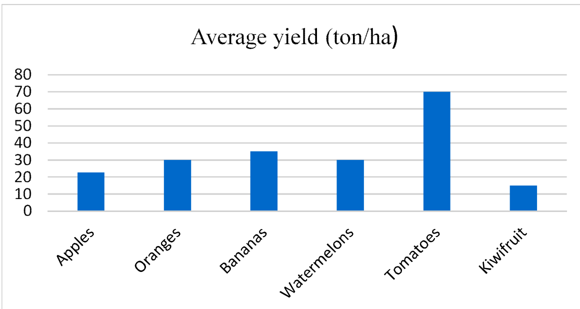

Fig. 1: Average yield of six crops: Apples, Oranges, Bananas, Watermelons, Tomatoes, and Kiwifruit (Pesteanu and Gudumac 2008; Zamora et al. 2010).

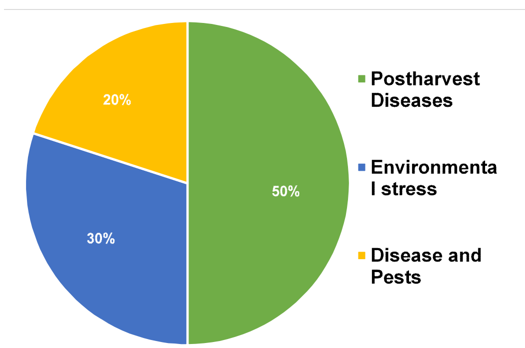

Fig. 2: Yield loss contributions in horticultural fruits (Wu et al. 2023).

In spite of their high yields, 15% to 70% losses in yields occur due to improper harvesting, packaging, and storage (Etefa et al. 2022; Bisht and Singh 2024). For instance, diseases such as Citrus huanglongbing (HLB) reduce yield by up to 19% yield through premature induced fruit drop and lowered fruit weight (Bassanezi et al. 2011). Unfruitfulness also, internally (self-incompatibility) and externally (extreme weather), results in low fruit set (Wani et al. 2010). Physiological disorders, nutritional deficiencies, and environmental stresses are factors that contribute to the exacerbation. There are many contributors responsible for the losses of horticultural commodities (Wu et al. 2023), a graphical illustration of the relative contribution of each factor to postharvest loss of fruits (Fig. 2).

Among these challenges, the Integrated Disease Management (IDM) is a key factor for action. Which starts with the identification of fungal pathogens, their symptoms, and host specificity. This review then move forward to cover fungal diseases detection technologies, comprising traditional-style microscopy to newly emerging molecular and non-destructive techniques. At last, the manuscript covers a broad range of prevention strategies, including cultural approaches, chemical and biological control measures, and integrated disease management systems.

This review comprises a critical synthesis of prevention and detection as the foundation for a successful response to threats from fungi of kiwifruit, other horticultural fruits, and vegetables. The review fills the gap between scientific research and horticultural practice in an attempt to promote sustainable crop protection against emerging threats.

2. Diseases of Horticultural Crops

2.1. Fungal Diseases

Fungal diseases in horticultural crops significantly impact yield and quality due to their diverse range of pathogens, targeting plant components like leaves, stems, roots, and fruits, posing a challenge in the field. There are mainly two types of pathogens that harm horticultural crops: biotrophic, which require living host tissue to thrive, and necrotrophic, which kill host tissue to obtain nutrients (Mahadevakumar and Sridhar 2021). Horticulture in recent days has become an important driver for the economic development of developing countries. Numerous fungal diseases threaten the production and productivity of the horticultural fruit trees (Table 1, Fig. 3).

Also, the table of common fungal diseases of horticultural vegetable crops, their causal agents, and their impacts on plants is provided in Table 2 and Fig. 4. As an example, gray mold caused by *Botrytis cinerea* is famous for wreaking havoc on tomatoes, peppers, cucumbers, and lettuce. Downy mildew and early blight are also listed with broad crop associations and symptoms. The expressions of the disease symptoms are in the last stage; before that, it is necessary to understand the development of the fungal spore of the individual fungal diseases in vegetable crops (Fig. 5).

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A. Grape Black Rot


B. Peach canker


C. Peach leaf curl


D. Powdery Mildew (Apple)


E. Apple Scab


F. Anthrosnose (Mango)


G. Spur Blight (Raspberry)


H. Brown Rot (Cherry)

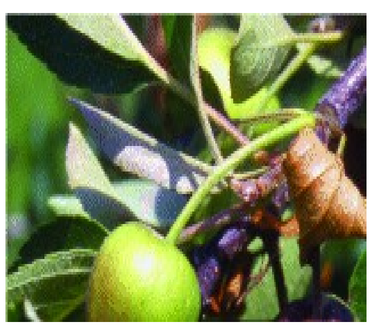

I. Black Knot


J. Verticillium wilt


K. Leaf spot (cherry)


L. Phytophthora root rot


M. Bull's eye rot


N. Fire blight


O. Leaf rust

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P. Blue Mold

Q. Gray Mold

R. Bitter rot

S. Sooty Blotch (Citrus)

T. Sooty Blotch (Apple)

Fig. 3: [A-T] Fungal diseases of major fruit tree crops.

Table 1: Common fungal diseases of Fruit crops

S.N.	Name of diseases	Fungal agent	Crop plant	Symptoms	References
1	Grape Black Rot	*Guignardia bidwellii*	Grapes	Small yellowish spots on leaves ,adark border forms around the margings after afterward when enlarging spots	Szabó et al. 2023
2	Peach Canker	*Cytospora leucostoma*	Apricot, prune, plum and sweet cherry	Gummy drops of sap around wounded bark	Reddy 2016; Schnabel & Brannen 2022
3	Peach leaf curl	*Taphrina deformans*	Peach, nectarine and ornamental plants	Leaf curling and discoloration, yellow, orange, red or purple color.	Schnabel & Brannen 2022
4	Powdery Mildew	*Podosphaera leucotricha.*	Apple, Pear, Straberry, Grapevine	White powdery spots develon on both leaf surfaces, leaves turn yellow or brown and fall off, develop weblike russet scars or corky areas	Pierson et al.1971; Reddy 2016; Goyal et al. 2020
5	Apple Scab	*Venturia prima*	Apple, Peaches, Cherries, Plum, Apricot	Dark blotches or lesions on the leaves,fruits and young twings, twisted and puckered leaves with black circular scabby spots on the underside.	Pierson et al.1971; Reddy 2016; Shafi et al. 2019
6	Anthracnose	*Colletotricum spp.*	Mango, Papaya, AvocadoRaspberry, Blackberry	Leaf spots,twig and fruit blight,sunken spots on the fruit,and twig dieback.	Pierson et al.1971; Siddiqui & Ali 2014; Reddy 2016
7	Spur Blight	*Didymella applanata*	Raspberry	Dark indistinct spots, either brown or purple just below the point where a leaf attaches to the cane.	Pierson et al. 1971
8	Brown rot	*Monilinia fructicola*, *Monilinia fructigena*, and *Monilinia Laxa*	Stone fruits (Cherry, Apricot, peach, nectarine, plum)	Small, round brown spots on the fruti surfaces,twig blights and twig canker,blossom blight and mummified fruits.	Pierson et al. 1971; Sardella et al. 2016
9	Black knot	*Apiosporina morbosa*	Pulums and cherries	Dark knots, leaves wilting, mishappen or blemished fruits and bieback	Pierson et al. 1971; Sardella et al. 2016
10	Verticilium Wilt	*Verticillium dahliae*, *Verticillium albo-atru*	Strawberries, caneberries, and stone fruits	Wilting, yellowing and plant death	Pierson et al.1971; Garrido et al. 2016
11	Leaf spot	*Glomerella cingulata*	Strawberry, cherrrry, plum, Apple	Pale yellow, Olive green and dark velvety spots	Pierson et al.1971; Liu et al. 2016
12	Phytophthora root rot, crown root rot	Genus *Phytophthora*	Stone fruits (Cherry, Apricot, peach, nectarine, plum)	Water -soaked spots on the crown that expand and girdle the stem, wilting, root become dicolored and rotten.	Pierson et al.1971; Sardella et al. 2016
13	Bull's eye rot	*Neofabraea spp*	Apple	Light brown centers and a dark brown border	Pierson et al.1971; Henriquez et al. 2008
14	Fire blight	*Erwinia amylovora*	Apple and Pear	Red, brown or black, may be outward in wood	Pierson et al.1971
15	Leaf rust	*Phakopsora montana*, *Phakossora euvitis*	Grape vine	Angular brown spots on the top side of the leaf.	Pota et al. 2015
16	Blue mold	*Penicillium expansum*, *Penicillium spp.*	Pears, Apples	It occurs on fruits during storage and transit, fruits become watery, Wetery spot increases then entire fruit rots, emits bad smell.	Pierson et al. 1971; Monroe 2009
17	Gray mold	*Botrytis cinerea*	Strawberries, Pears, grapes	All varieties that are stored for long periods	Pierson et al.1971; Monroe 2009
18	Bitter rot	*Colletotricum spp.*	Apples, Pears	All varieties (mostly pears that start to ripen)	Pierson et al.1971; Monroe 2009
19	Sooty blotch	*Peltaster fructicola*, *Leptodontium elatius*	Bananas, Pears, Citrus, Apples	Olive green to dull black sooty blothces appear on near mature fruits, blotches may coalesce to cover practically the entire fruit.	Ellis 2008

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Table 2: Common fungal diseases of vegetable crops

S.N.	Name of diseases	Fungal agent	Crop plant	Symptoms	Ref.
1	Damping-off	*Pythium, Fusarium, Rhizoctonia*	Beans, Brassicas, cucurbits, lettuce, peppers, and tomatoes	Seedlings (causes collapse and death)	Szabó et al. 2023
2	Downy Mildew	*Phytophthora infestans, Bremia lactucae, Pseudo-peronospora cubensis, Peronospora menshurica*	Potatoes, Tomatoes, Lettuce, Cucurbits, Soybean	Upper (light green spots) and lower (greyish/beige downy tufts)on leaf surface.	Wu 2020; Schnabel & Brannen 2022
3	Early blight	*Alternaria solani,Alternaria tenuis*	Potatoes, Tomatoes	Leaf spots ,defoliation	Pierson et al.1971
4	Gray Mold	*Botrytis cinerea*	Tomotoes, peppers, cucumbrrs, little	Fruit rot	Dai et al. 2022
5	Powdery Mildew	*Erysiphae cichoracearum , Erysiphepisi,and related species*	Cucumbers, Peaand other crops	White powdery spot on leaves, Brownish spots on leafs	Aravindaram Kandan et al. 2016; Goyal et al. 2020
6	Fusarium Wilt	*Fusarium oxysporum*	Tomatoes, peppers, cucumbers, Chick Pea, Eggplant	Wilting, plant death, Grayish -geen chlorosis, typically affecting lower leafs first and extending up the plant	Shafi et al. 2019; Szabó et al. 2023
7	Verticilium Wilt	*Verticillium* species	Wide range of crops	Wilting and yellowing of leaves	Siddiqui & Ali 2014
8	Anthracnose	*Colletotrichum sp., Gloeosporium sp., and Discula destructiva.*	Beans, Lettuce, Pea, Toamto, Cucumber, Watermelon, Pumpkin, Potato	Leaf spots ,defoliation	Sardella et al. 2016
9	Leaf blight	*Alternaria dauci and Cercospora carotae*	Carrot	Brownish spot on leaf	Zamora et al. 2010
10	Late blight	*Phytophthora infestans,*	Potatoes, Tomatoes, and Eggplants	Dark water soaked lesions on leaves and stems, Pale green spots. white fluffy growth on the undersides of the leaves	Otero et al. 2007
11	Leaf spot	*Cercospora sojina,Cercospora capsici,C.melongenae*	Soyabean, Pepper, Eggplant	Dark brown centers with red or dark reddish margins	Zambounis et al. 2020

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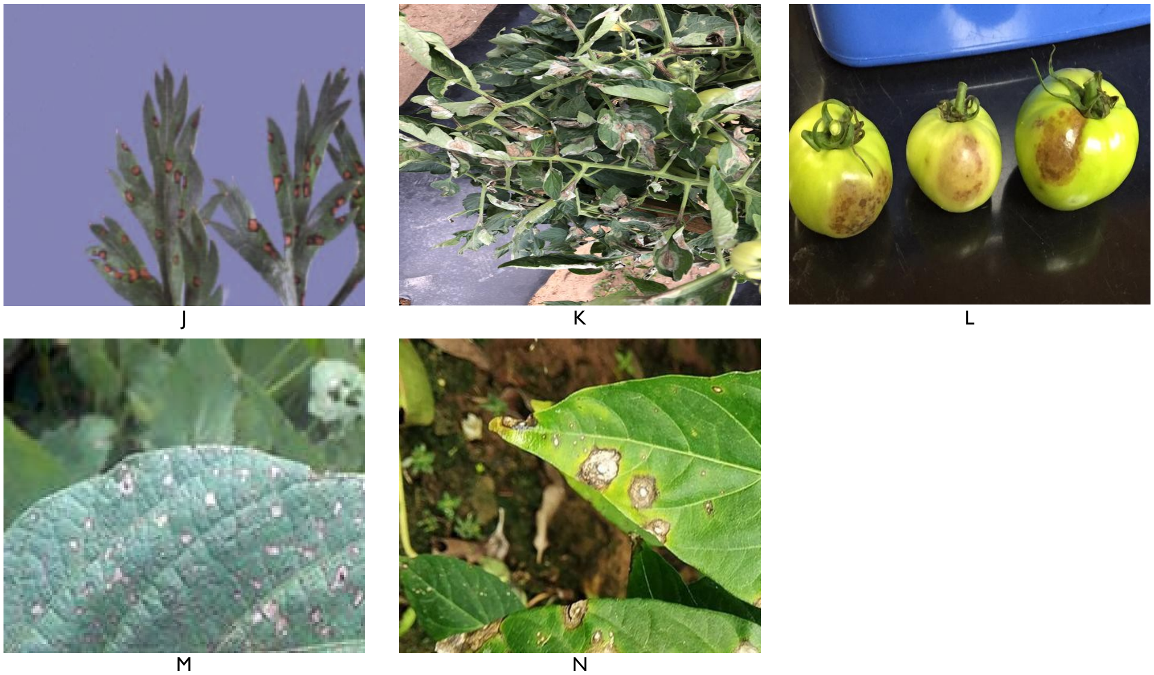

Fig. 4: Disease infection symptoms of various horticultural crops (A) Damping off in cucumber (B)Downy mildew of cucurbits, (C) Early blight in Tomato, (D)Gray mold, (E)Powdery mildew of cucurbits, (F) Fusarium wilt in tomato, (G) Anthracnose in chilli, (H) Verticillium wilt(I)&(J) Leaf blight in Carrot(K)&(L)Late blight in Tomato,(M)&(N)Leaf spot.

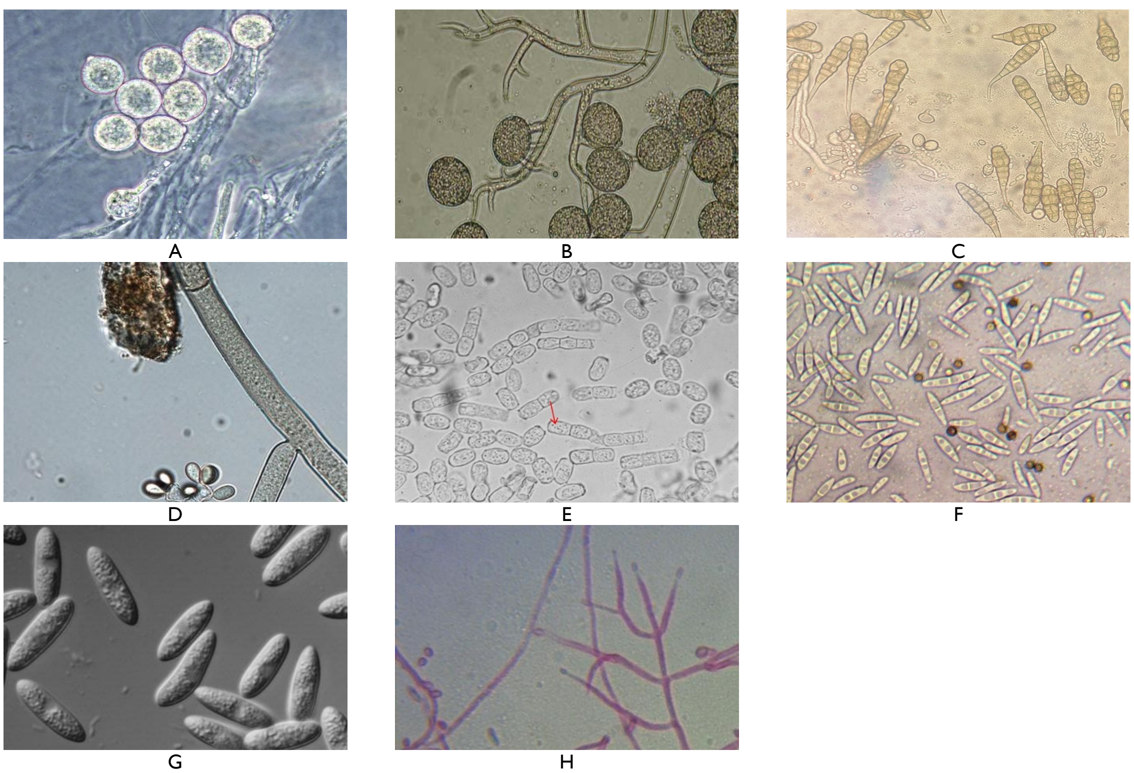

Fig. 5: Fungal spores of various fungal diseases of horticultural crops (A)Damping off fungal spore (*Pythium spp.*),(B)Downy mildew fungal spore (*Pseudoperonospora spp*.),(C)Early blight fungal spore (*Alternaria spp*.), (D)Gray mold fungal spore (*Botrytis spp*.),(E) Powdery mildew fungal spore (*Erysiphe spp*.),(F)*Fusarium* Wilt ,Fungal spore,(G) Anthracnose fungal spore (*Colletotrichum spp*.),(H) *Verticillum* spore.

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Though importance has been assigned to such pathogenic fungi, reference should be made to the observation that other non-pathogenic fungi also might constitute a part of the kiwifruit microbiome and influence disease dynamics and disease management strategies (Huang et al. 2023). *Botrytis cinerea* is a highly prevalent and destructive fungal pathotype whose drastically adverse impact on kiwifruit production and quality is well demonstrated in Table 3, Fig. 6, caused by gray mold rot (Dai et al. 2022; Haghbin et al. 2023). Identification of *Verticillium nonalfalfae* MLST2 as a highly virulent fungus, particularly in Chile, represents a rapidly emerging threat with the possibility of global distribution via germplasm exchange (Lee et al. 2022). Furthermore, *Aspergillus japonicus*, *Aspergillus flavus*, and *Penicillium oxalicum* have also been found to be primary causative fungi of kiwifruit rot (Huang et al. 2023). Kiwifruit vine decline syndrome (KVDS) is a polyfactorial disease controlled by a range of causes, such as the oomycete *Phytopythium*, a range of bacterial and fungal communities, geoclimatic factors, soil factors, and rhizosphere microbiome disequilibrium (Guaschino et al. 2024).

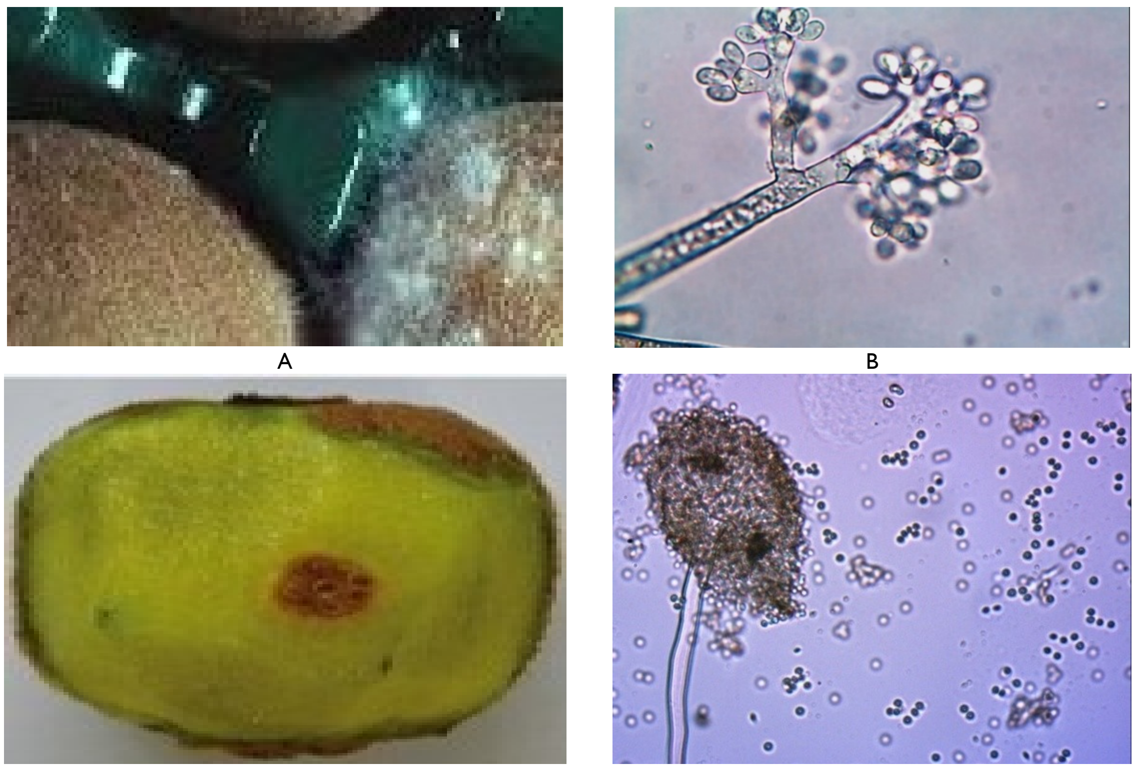

Fig. 6: Fungal disease infection symptoms and fungal spores in Kiwifruit (A) *Botrytis* rot in Kiwifruit, (B) *Botrytis cinerea* spore, (C) *Aspergillus* rot in Kiwifruit, (D) *Aspergillus spp.* spore.

Table 3: List of fungal diseases in Kiwifruit

Disease	Causal Organism	Affects	Reference
Botrytis Rot	*Botrytis cinerea*	Postharvest decay (botrytis rot)	Dai et al. 2022
Aspergillus Rot	*Aspergillus japonicus, Aspergillus flavus*	Postharvest decay	Huang et al. 2023
Penicillium Rot	*Penicillium oxalicum, Penicillium expansum*	Postharvest decay	Dai et al. 2022; Huang et al. 2023
Kiwifruit Rot	*Botryosphaeria dothidea*	Rot in kiwifruit	Ren et al. 2022
Kiwifruit Rot	*Dothiorella gregaria*	Rot in kiwifruit	Ren et al. 2022
Kiwifruit Trunk Disease (KTD)	*Neobulgaria alba Chaetomium sp.*		Tyson & Mellow 2024
Market disease	*Phomopsis vaccinii*	Sunken peels and yellow pulp	Li et al. 2015

Didymella glomerata causes black spot disease, leading to serious losses during fruit growth (Wang et al. 2022b). *Cadophora luteo-olivacea* and *Diaporthe eres* are the other leading causes of postharvest rot, impacting the economic viability of kiwifruit businesses, particularly in South Korea (Park et al. 2023). *Phomopsis vaccinii* is the key pathogen of imported kiwifruit, causing soft-rot lesions in markets in Shanghai. *Phomopsis* spp. is the most virulent, with the highest growth rate at 25°C (Li et al. 2015). Twenty seven *phialophora*-like fungi were defined, two of which were *Cadophora melinii* and *Lecythophora luteoviridis*, with three phenotypic types and striking fungal morphology, showing that elephantiasis disease is linked with kiwifruit's complex mycoflora (Prodi et al. 2008). Fungi isolated from symptomatic vines and asymptomatic vines, *Neobulgaria alba* and *Chaetomium* sp. respectively, led to Kiwifruit Trunk Disease (KTD) (Tyson & Mellow 2024). Several types of rot are caused by the pathogens *Sclerotinia sclerotiorum*, *Botrytis cinerea*, and *Botryosphaeria dothidea*, which may occur in the harvest and packaging process in Kiwifruit (Pennycook 1985).

2.2. Pathogen Detection Methods

Since the spread of the major fungal pathogens for infection in fruit crops and kiwifruit is on the increase, identification of the pathogens is necessary before irreparable harm is done. The prompt and accurate detection can efficiently prevent and control disease, thereby paving the way for targeted controls. The pathogen detection technologies are key in postharvest horticulture for minimizing economic losses and ensuring food security and safety. Numerous fungal pathogens are the main causes of postharvest rot, and therefore, early and actual detection tools are needed to counterbalance their impact (Udriste et al. 2018; Kgang et al. 2023). There are conventional diagnostic techniques, such as microscopy and visual inspection, which were complemented with high-sensitivity and high-specificity advanced molecular technologies like loop-mediated isothermal amplification (LAMP) and polymerase chain reaction (PCR) for pathogen detection in early stages (Udriste et al. 2018; Mellikeche et al. 2022). LAMP is also considered for speed and convenience, to the extent that certain genetic areas to synthesize mycotoxins and in detection of fungicide resistance are able to utilize basic equipment (Mellikeche et al. 2022). Moreover, non-destructive methods including spectroscopy and imaging are under development for use in the detection of insect infestation in fruit and are meeting consumer concerns around the use of chemicals as well as in compliance with quarantine requirements (Adedeji et al. 2020). Likewise, proteomics and bioassays are also in the pipeline as emerging technologies for asymptomatic disease stages detection with on-the-spot reporting to advance postharvest disease controls (Kgang et al. 2023). These technologies for pathogen detection not only promote the precise detection of disease stages but also advance less reliance on chemical controls, thereby advancing sustainable farming (Kgang et al. 2023). In general, the application of these new technologies can dramatically enhance postharvest disease controls and thus the safety and quality of horticultural commodities.

2.2.1. Traditional Methods: Various traditional methods were the initial methods utilized in the detection of fungal pathogens; nowadays, they have been replaced in specificity by newer techniques because of their wide application in low-resource regions. They are very significant in such locations. Their past use and accessibility have made them a foundation in disease monitoring programmes. Traditional methods of detecting fungal pathogens, such as visual evaluation and culturing, have been the cornerstone of disease diagnosis for many decades. Microscopy, culturing, and staining are fundamental approaches used to identify fungal pathogens in postharvest horticulture, particularly for fruits. Microscopic analysis allows for identification of the fungal structures and identification of pathogenicity as evidenced in studies on longan fruits, wherein a host of genera such as *Lasiodiplodia* and *Pestalotiopsis* were isolated and identified (Suwanakood et al. 2007). Techniques such as tissue transplanting allow for growth of such pathogens for later studies, while staining methods enhance increased visibility of the fungal components in the microscope (Suwanakood et al. 2007). While such approaches are cheap and not expensive, in most cases, they are labor-intensive, time-consuming and low in sensitivity. The visual inspections depend on observation of characteristic signs such as discoloration, lesions, or growth of mold. However, in most cases such signs are normally witnessed towards the later stages of the infection period, making early detection more challenging (Xu et al. 2022; Iradukunda et al. 2022). Various fungal pathogens are the main causes of postharvest rot, and so early and accurate detection tools are needed to counterbalance their impact (Udriste et al. 2018; Kgang et al. 2023).

Moreover, the conventional diagnostic techniques, such as microscopy and visual inspection, were complemented with high-sensitivity and high-specificity advanced molecular technologies like loop-mediated isothermal amplification (LAMP) and polymerase chain reaction (PCR) for pathogen detection in early stages (Udriste et al. 2018; Mellikeche et al. 2022). LAMP is also considered for speed and convenience, to the extent that certain genetic areas to synthesize mycotoxins and in detection of fungicide resistance are able to utilize basic equipment (Mellikeche et al. 2022). Likewise, non-destructive methods including spectroscopy and imaging are under development for use in the detection of insect infestation in fruit and are meeting consumer concerns around the use of chemicals as well as in compliance with quarantine requirements (Adedeji et al. 2020). In addition, proteomics and bioassays are also in the pipeline as emerging technologies for asymptomatic disease stages detection with on-the-spot reporting to advance postharvest disease control (Kgang et al. 2023). These technologies in pathogen detection not only promote the precise detection of disease stages but also advance less reliance on chemical controls, thereby advancing sustainable farming (Kgang et al. 2023). In general, the application of these new technologies can dramatically enhance postharvest disease controls thereby producing safety and quality of horticultural commodities. These examples emphasize the significance of immuno-technologies in enhancing the detection and disease control of fungal pathogens, thereby reducing postharvest losses in horticultural crops (Otero et al. 2007; Park et al. 2023).

Culturing methods, although more sensitive, require days to weeks to isolate and identify pathogens. Morphological identification via plating assays remains invaluable for diagnosing fungal infections but lacks the specificity needed to distinguish closely related fungal species (Lee et al. 2022). However, speed and sensitivity limitations continue to restrict its use in time-sensitive or high-volume applications.

2.2.2. Molecular Detection Techniques: There are various molecular detection technologies, including PCR, qPCR, and LAMP, which are a huge leap towards diagnostic efficiency and speed without most of the drawbacks of the earlier equipment. These technologies help in detecting pathogens before the symptoms. The recent advancement in molecular and genomics research has shed light on our understanding of the virulence and pathogenicity of these fungi (Dai et al. 2022; Ling et al. 2024). For example, the genome of *Diaporthe eres* P3-1W demonstrated an enormous quantity of information about its carbohydrate-active enzymes (CAZymes), a determining attribute of its pathogenicity (Ling et al. 2024). Indeed, the highest enzymatic activity of the cellulase, β-galactosidase, polygalacturonase, and pectin methylesterases was realized on the second day post-infection (Ling et al. 2024). It is only with such a high degree of information regarding the pathogen mechanism that more accurate detection and prevention technology can be made ready. Similarly, the creation of a GFP-labelled strain of *Botryosphaeria dothidea* becomes possible to deeply investigate the infection process in kiwifruit tissues (Liu et al. 2024b).

Molecular methods have revolutionized identification of fungal pathogens at high specificity, sensitivity, and short turnaround times. PCR and qPCR are used routinely for the identification of fungal DNA, even in asymptomatic stages (Prodi et al. 2008). They employ pathogen-specific primers for gene amplification and have the ability to detect with high accuracy. With the support of recent technologies, for example, multiplex qPCR tests, a number of pathogens are identified concurrently in a single session, therefore enhancing efficiency as well as reducing costs (Chen et al. 2022; Romero-Cuadrado et al. 2024).

In comparison to conventional PCR, Loop-mediated isothermal amplification (LAMP) and Recombinase Polymerase Amplification (RPA) have been developed as fast, portable substitutes (Udriste et al. 2018). Having 6-30 minute detection times, and good specificity and sensitivity to various pathogens and various sample matrices, specific and sensitive LAMP assays were developed for conditions such as capsicum (*Colletotrichum capsici)*, avocado (*Calonectria ilicicola),* and grapes (*Dactylonectria macrodidyma)*, and banana (P*seudocercospora eumusae*) (Aravindaram Kandan et al. 2016; Thangavelu & Devi 2018; Parkinson et al. 2019). For instances, for *Pseudocercospora eumusae* LAMP assay had 10 pg/µl detection capacity, many times higher than that of regular PCR (Thangavelu & Devi 2018). Likewise, RPA and LAMP were also shown to be compared for the detection of plant pathogens such as *Botryosphaeria dothidea* and *Phytophthora cinnamomi* with higher sensitivity, and specificity (Wang et al. 2021; Haghbin et al. 2023). Besides molecular methods, there is new technology coming up every day to detect pathogens at an early stage. There was development of a laser-induced fluorescence spectroscopy-based remote detection system, vinoLAS, for detecting fungal infection in grapes early (Kölbl et al. 2023). Metagenomics also investigates the structure of the fungal communities within fruits, with identification of dominant pathogens and their intercorrelations (Zambounis et al. 2020).

However, the literature demonstrates a significant gap in single PCR-based studies for the detection of fungal pathogens on a wide range of fruit crops such as apples, kiwis, and citrus. Even though some studies have been conducted on apple pathogens through the use of qPCR and LAMP for the early detection of *Monilinia* spp. and *Venturia inaequalis* (Udriste et al. 2018), and on kiwifruit pathogens such as *Cadophora luteo-olivacea* with SCAR primers, there are no comprehensive studies in which many fruit crops are taken into consideration at the same time. Moreover, whereas multiplex PCR methods are described for berry pathogens, similar methods for a wide range of fruit crops are not well investigated. Such a gap necessitates further targeted research in an effort to push the detection and control of fungal pathogens across a broad array of food species for food safety and minimization of horticulture economic losses. As much as molecular techniques are highly sensitive, they are sophisticated and could require infrastructure and technical experts, hence being unfeasible in all circumstances. Due to the consequences of these, there was increased interest in non-destructive technologies to combine efficiency and practicability.

2.2.3. Non-Destructive Methods: There are numerous non-destructive methods which offer a hi-tech alternative due to the numerous reasons including detection of pathogen at an early stage, achievable without damaging produce, optimal for maintaining market value, and shelf-life enhancement. Hyperspectral imaging and electronic noses (E-nose) are just two instances of the wave of more intelligent, non-destructive monitoring equipment. Imaging and spectroscopy, and hyperspectral sensors in particular, have evolved as effective non-destructive techniques for the detection of fungal pathogens in postharvest fruit. Hyperspectral imaging (HSI) and e-nose technology are the new pre-symptomatic diagnostic techniques (Lv et al. 2023). HSI takes advantage of spatial and spectral information to identify infected tissues much earlier than symptomatic expressions, with discrimination accuracy greater than 96%

for kiwifruits infected with *Botrytis cinerea* (Haghbin et al. 2023). Hyperspectral imaging (HSI) identifies the fungal diseases by examining the spectral signature within a certain wavelength in a way that infection is identified even before the appearance of visible signs. For instance, it is the fact that based on studies it has been discovered that HSI identifies fungus-infected rotten oranges with a highly satisfactory accuracy, that is, 100% accuracy in case of certain pathogens (Yin et al. 2017). GLCM and GLRLM are techniques utilized in the image processing of gray mold infected fruit with a high classification rate (Pujari et al. 2013). E-nose technology that identifies volatile organic compounds discharged by pathogens has been utilized for the early detection of gray mold and fruit soft rot (Wang et al. 2023). Fungal mango diseases are diagnosed via x-ray imaging technology without causing damage to the fruit, and grading and quality checking can be performed. Enzyme-Linked Immunosorbent Assays (ELISA) identify early latent infections, such as mango anthracnose, by detecting characteristic antigens (Theerthagiri et al. 2016; Dhondiram &Ashok 2017).

Imaging and spectroscopy, particularly hyperspectral sensors, play a critical role in non-destructive postharvest diagnosis of fungal fruit disease such as peach, kiwifruit, and orange diseases. Imaging and spectroscopy enable infection detection at the first stage prior to symptom development, which maximizes the effectiveness of postharvest management (Liu et al. 2020; Haghbin et al. 2023). There are some non-destructive methods, including hyperspectral imaging (HSI), which are applied to estimate precisely the degree of fungal spoilage with accurate prediction and classification power using advanced chemometric models (Yin et al. 2017; Liu et al. 2020; Haghbin et al. 2023). It has disadvantages, including that large-scale calibration needs to be done and spectral information can change based on the surface characteristics of fruits, which may complicate analysis (Yin et al. 2017; Lu & Lu 2017). Likewise, the promise of these methods must be complemented by sophisticated data processing and analysis, which are typically not prevalent in most working settings (Lu & Lu 2017; Tephillah et al. 2024). In general, application of these non-destructive methods has enormous potential to improve fruit quality and safety in agriculture. While extremely promising, these tools also present barriers to access in terms of affordability and ease of use. Comparing all the available methods side by side helps determine the most suitable ones for various agricultural conditions.

2.2.4. Comparison between different detection methods: There are various methods of detection of fungal pathogens in horticultural commodities. As mentioned earlier, conventional, molecular, and non-destructive methods are known in these categories, and many newer techniques are emerging day by day. A comparative brief description of different methods, their detection speed and accuracy, field applicability, and detection stage is given in Table 4.

Table 4: Comparisons among different detection methods (Xu et al. 2022; Park et al. 2023; Haghbin et al. 2023; Wang et al. 2023; Romero-Cuadrado et al. 2024)

Method	Sample type	Sensitivity (LOD)	Speed	Accuracy	Field Applicability	Stage of Detection
Visual Inspection	Whole plant	Low	Slow (> 24 hours	Low	High	Late
Culture-Based Methods	Plant tissue, soil samples	Moderate	Very slow (3-7 days)	Moderate	Moderate	Intermediate
Biochemical Analysis	Plant extracts	Variable	Moderate (4-6 hours)	Moderate	Limited	Intermediate
PCR / qPCR	DNA from plant tissues	~1 pg DNA	Fast	High	Moderate	Early
LAMP / RPA	DNA/RNA from plant tissues	100–1000× more sensitive than PCR	Fast	High	High (portable kits)	Early
Hyperspectral Imaging (HSI)	Whole plant, fruits	High	Fast	Very high	Moderate	Pre-symptomatic
Electronic Nose (E-nose)	Whole plant, Fruits	High	Fast	High	High	Early
ELISA	Plant sap, tissue extracts	Variable	Fast	High	Moderate	Early
X-ray Imaging	Whole fruits	Moderate	Fast (30-60 Minutes)	High	Low (expensive)	Early to Intermediate
Metagenomics	DNA from plant tissues	Very high	Slow (Days to weeks)	Very high	Research only	Any

The comparison also illustrates that no single method is universally superior; the choice depends on context, cost, and purpose.

2.2.5. Merits and Demerits of Traditional and Advanced Detection Methods: Before the emergence of novel technologies of detection of fungal pathogens and protection of horticultural crops i.e., molecular methods of detection and non-destructive technologies, traditional methods like visual symptom and culturing were supposed to

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be filling front-line roles, but now these are cornerstones which do not deserve the top priority. Furthermore, advanced detection techniques also possess some disadvantages. Discussed below are the merits and demerits of traditional and new detection methods of fungal horticultural crop pathogens. Knowledge of such trade-offs is relevant to implementing effective detection programs. But technical barriers and adoption challenges still limit widespread use.

2.2.5.1. Traditional Methods

Merits:

- Cost-effective and do not require advanced equipment (Reddy 2016).
- Suitable for field use in low-resource areas (Udriste et al. 2018).
- Culturing allows for isolation and further study of the pathogen (Tan et al. 2023).

Demerits:

- Time-consuming, often requiring days to weeks for results.
- Low sensitivity and specificity; misdiagnosis is possible due to symptom overlap.
- Cannot detect pathogens at asymptomatic or early infection stages (Xu et al. 2022)

2.2.5.2. Advanced Detection Methods

Merits:

- High sensitivity and specificity: PCR, qPCR, and LAMP can detect pathogens at minimum levels **(**Romero-Cuadrado et al. 2024; Park et al. 2023**)**
- Enable early detection before symptoms appear (Haghbin et al. 2023).
- Some methods are non-destructive, preserving fruit for sale or further analysis (Wang et al. 2023).

Demerits:

- Require skilled manpower, technical infrastructure, and often costly reagents (Yaşa et al. 2018).
- Limited field-portability for methods like metagenomics or HSI (Kölbl et al 2023).
- Dependence on database completeness for molecular identification (Zambounis et al. 2020).

2.3. Challenges & Limitations

Despite technological innovation, the majority of detection systems are hindered by cost, technical requirements, and field readiness. These drawbacks must be overcome to increase fungal detection globally.

Certain challenges and limitations exist in efficiently and effectively detecting and preventing fungal diseases; recognizing these challenges also offers an opportunity for innovation and development.

Subsidiary technologies for the detection of advanced plant pathogens as promising as they are face several concerns that limit their widespread use. Cost and infrastructure are among them, given that techniques such as metagenomics and hyperspectral imaging are still too expensive to use on a daily basis (Xu et al. 2022; Haghbin et al. 2023). qPCR and sequencing devices, for instance, also require expertise, and this is not always available in infrastructure-poor settings (Romero-Cuadrado et al. 2024). Portability is also an issue since advanced devices are not typically designed for field use (Wang et al. 2023). Non-standardized protocols are equally a top priority concern, low reproducibility and laboratory-to-laboratory comparison being a problem (Park et al. 2023). Small manufacturers and farmers are not always eager to embrace such technologies as well, the complexity and operation requirement being a factor (Yaşa et al. 2018). Finally, the scarcity of finished and annotated reference genomes degrades DNA-based pathogen typing integrity, limiting molecular diagnostic precision (Ling et al. 2024).

2.4. Summary of Economically Viable Detection Methods

After discussion about the different disease detection methods and their comparative efficacy for the detection and prevention of fungal diseases, Table 5 presents a summary of efficacy and some features related to economically viable methods for the prevention and detection of fungal diseases in horticultural commodities. When considering large-scale deployment, cost-effectiveness, speed, and ease of use become critical. It is crucial to identify which detection tools are most feasible for field adoption, especially in resource-constrained settings.

Table 5: Economic viability of different detection methods

Method	Accuracy	Cost	Field Friendly	Reuse Potential	Verdict
LAMP	High	Low-Mid	Yes	Yes	Recommended
RPA	High	Low-Mid	Yes	Yes	Recommended
E-nose	Moderate	Mid	Yes	Yes	Recommended
Visual Inspection	Low	Very Low	Yes	Yes	Limited use
ELISA	High	Low	Yes (lab)	No (single use)	Recommended
qPCR / Metagenomics	Very High	High	No	No	Not economic

Briefly, an integrated detection strategy, combining traditional reliability with novel accuracy and non-destructive innovation, is the direction to follow to secure horticultural commodities. The technologies not only aid in disease diagnosis but also lead directly to the next step of management and prevention.

3. Pathogen Prevention Strategies

After effective detection of pathogens, active and comprehensive prevention becomes an imperative for long-term disease management. The use of resistant cultivars during fruit production is a key method for controlling fungal diseases that significantly affect quality and yield. Research underscores the necessity of breeding schemes to develop cultivars with genetic resistance to specific pathogens, e.g., strawberries with resistance to anthracnose and *Phytophthora* root rot, identified using molecular markers (Keldibekova et al. 2024). Similarly, adoption of resistant citrus cultivars has shown promising economic benefits, particularly in disease management such as citrus greening, where timing is necessary (Cui et al. 2025). Furthermore, organic strawberry production has also been made possible by the development of resistant types against *Botrytis cinerea* and *Xanthomonas fragariae*, which are part of sustainable agriculture (Bestfleisch et al. 2012). Traditional apple varieties have been found to resist apple scab and powdery mildew, and this shows that both new and old varieties can be part of organic farming systems (Papp et al. 2016). Breeding resistant kiwifruit varieties is critical in managing the myriad fungal diseases, but most importantly canker and brown spot diseases incited by *Pseudomonas syringae* and *Corynespora cassiicola*, respectively. Literature indicates that breeding for resistance varieties is an ultimate strategy considering that most of the existing varieties lack the necessary resistance genes (Su et al. 2024). For instance, research has identified several cultivars with varying degrees of resistance, e.g., 'Jinkui' and 'Zhonghua Soft,' which are highly resistant to bacterial canker, whereas 'Hayward' is moderately susceptible (Miao et al. 2004). These experiments emphasize the importance of a diversified strategy towards the enhancement of disease resistance in fruit crops.

Significant fungal diseases harm the quality of kiwifruit, particularly yellow- and red-fleshed cultivars that are more prone (Kim & Koh 2018). Integrated management practices need to be implemented to prevent such diseases. Humidity increases stimulate fungi growth in stored kiwifruits, but controlled atmospheres effectively retard ripening. Proper handling practices are necessary in disease control (Sommer et al. 1983).

Effective prevention techniques are critical in combating fungal diseases in horticultural produce and kiwifruit. These techniques involve cultural practices, chemical control, biological control, and environment-friendly approaches that prioritize sustainability and minimize dependence on chemical fungicides.

3.1. Cultural Practices

Low-cost and straightforward controls of fungal spread through orchard management, field sanitation, and environmental management are cultural practices. They are able to significantly control prevention of primary inoculum and harmful conditions for survival by pathogens. Preharvest pruning, soil nutrients, and water management have a vital impact on postharvest fruit fungal disease avoidance. Pruning in proper time enhances penetration of light and air circulation, low humidity for induction of growth by fungi, and good water management to prevent excess water that leads to rotting of fruits (Grahovac et al. 2011). Moreover, the health of the soil is also given emphasis because it will dictate the health and resistance of the crops to pathogens; healthy soils with well-developed root systems can withstand stress and infection by pathogens (Gao et al. 2018). Also utilized is the use of biocontrol agents, i.e., yeast and antagonistic bacteria, in pre-harvest management that has been proven to induce resistance to postharvest diseases and consequently reduce levels of incidence by a considerable degree (Wang et al. 2022). The practice can also limit economic loss as well as enhance the quality of the fruit upon storage (Schirra et al. 2011; Godana et al. 2023).

Cultural practices are the cornerstone of disease management by creating an unsuitable environment for growth and development of fungi. Important cultural practices include conditioning the environment for growth, temperature, humidity, and ventilation to inhibit growth of the pathogen. Sanitation measures, removal of infected material, disinfecting storage area and equipment, and minimizing mechanical damage during handling are all crucial in inoculum level management. Besides that, hot water, hot steam, and hot air are effective methods for fungi, insects, and management of fungal pathogens (Yaşa et al. 2018). Buds are a cost-saving technique used under commercial Kiwifruit production for multiplication of new types and removal of old ones, facilitating homogeneity and quality and enabling rapid introduction of superior and resistant types (Rai & Rai 2024a). Grafting is among the methods that escapes biotic stress resulting from Nematodes and fungi in the soil, minimizes reliance on chemical substances, and possesses greater low-temperature tolerance of soil (Rai & Rai 2024b).

Crop rotation is another cultural practice that effectively breaks the life cycle of soilborne fungal pathogens (Holb 2009) and equally while shifting from conventional production systems to organic bio-intensive production systems (Rai et al. 2024; Shrestha et al. 2024). Orchard and pre-harvest sanitation practice can effectively reduce post-harvest fungal infection of kiwifruit (Mitidieri et al. 2021). Besides, the control of irrigation is needed; not too much wet because it causes the development of fungus, particularly for the case of fruits that contain lots of water.

There are various techniques, including routine scouting and application of forecasting equipment, that play a key role in early diagnosis and intervention techniques that are accountable for postharvest management of fungal fruit diseases. Though the pathogens can be detected early using this equipment, this is a phenomenon that is vital in reducing economic loss during transportation and storage. Likewise, the application of physical treatments such as heat treatment combined with biocontrol agents may confer resistance to rotting of fruits as well as enhance storage quality (Schirra et al. 2011). They both emphasize the importance of anticipatory management in the prevention of postharvest fungal disease.

Application of antagonistic microbes like yeasts and bacteria would suppress fungal pathogens through competition with inhibitory chemicals and space (Oztekin et al. 2023; Dukare et al. 2021). It would also qualify as biological control but would be more of the cultural or traditional kind. Cultural methods cannot be substituted but would probably not work well under high disease pressure. Chemical control would therefore be applied to physically suppress fungal activity in such cases.

3.2. Chemical Control

Chemical fungicides are having speedy and efficient control over the majority of fungal diseases. They are used on a wide scale in conventional farming, particularly where speedy control is necessary to protect yields and marketability. Chemical fungicides continue to be used widely in horticulture to control fungal diseases. Azoles, such as tebuconazole and propiconazole, are used frequently because they possess broad-spectrum activity and prolonged persistence. But environmental toxicity, human health risks, and fungicide resistance need to be used cautiously (Jørgensen and Heick 2021). Gum-based nanocomposites provide a physical barrier against fungal infection and senescence of fruits. They can be loaded with active components like essential oils and metal ions to confer fungistatic activity. Phenyl tetramethyl cyclopropane carboxamide (PTCC) class of compounds has promise as low-toxicity broad-spectrum fungicides. They regulate fungal membrane polarity and metabolism, reducing pathogen viability (Duanis-Assaf et al. 2023).

For kiwifruit, fludioxonil and fluazinam chemicals have managed pathogens like *Botrytis cinerea* and *Penicillium* spp. However, the resistance development, particularly with pathogens like *Alternaria alternata*, has led to suggestions for incorporating management programs with both chemicals and non-chemical methods (Wang et al. 2022). AoH25@β-CD, having 88.5% fungicidal activity against soft rot of kiwifruit, outperforms fluopyram and azoxystrobin with optimum EC50 values and wide-spectrum bioactivity against a wide range of fungi (De Matos Fonseca et al. 2024). Calcium chloride treatment reduced weight loss to 12.65%, increased juice recovery to 22.64%, and maintained quality for 16 days compared to control tomatoes with the highest acidity and lowest pH (Subedi et al. 2024). Though effective, they can lead to resistance and environmental risk when misused. This calls for research into safer and more environmentally friendly alternatives, such as biological control agents.

3.3. Biological Control

Biological control harnesses beneficial microbes that antagonize fungal pathogens, offering an eco-friendly solution to disease management. This strategy supports the shift toward sustainable horticulture and is especially valuable for sensitive crops like kiwifruit. Some biocontrol agents, like *Trichoderma* spp. (Almeida et al. 2024), *Pseudomonas* spp. (Gao et al. 2018), and *Bacillus velezensis* (Arabzadeh et al. 2023), have shown excellent efficacy against fungal infections. The mode of action of these microorganisms is through other mechanisms, that is, mycoparasitism, competition for nutrients, and the formation of antifungal metabolites (Gao et al. 2018; Rees et al. 2022; Kolytaitė et al. 2022; Arabzadeh et al. 2023; Deng et al. 2024). Use of biocontrol agents is practicable via various mechanisms including seed treatment, soil drenching, foliar spraying, and the addition to bioactive coatings (Woo et al. 2014; Błaszczyk et al. 2022). Fungal Volatile Organic Compounds (FVOCs) are potential biocontrol agents as they are non-toxic and environmental-friendly. They work through the modification of the cell structures of fungi and disrupt cellular processes, leading to cell death (Napitupulu 2023). Biocontrol strategies involving microbial antagonists are also being discovered as an effective alternative to synthetic fungicides because they regulate pathogens and restrict chemical usage (Ray et al. 2011; Godana et al. 2023).

Different studies have indicated that combining biological with physical/chemical control can enhance the effectiveness of biological control. Specifically, the combination of *C. oleophila* and an oligogalacturonide resulted in a superior synergy compared to their individual applications as kiwifruit postharvest disease control (Gao et al. 2021). The interaction among *Candida diversa* and harpin treatment has been demonstrated to be a greater level of kiwifruit control when either treatment was used individually. This interaction has been demonstrated to be a point where defense-related enzymes are upregulated in treated kiwifruit, amongst others (Tang et al. 2015). Bacteria with antagonistic activity, ranging from prokaryotic to eukaryotic microorganisms, have varying levels of performance against generic fruits and vegetables. In vitro research and fresh-keeping techniques with these bacteria have improved the post-harvest quality of vegetables and fruits, demonstrating their potential to be a good use in pest control (Li et al. 2022).

Fusicolla violacea and *Meyerozyma guilliermondii* have shown promise in controlling soft rot caused by *Alternaria alternata* in Kiwifruit. Similarly, *Pseudomonas synxantha* volatile organic compounds (VOCs) effectively inhibit the growth of a significant postharvest pathogen, *Cadophora luteo-olivacea* (Di Francesco et al. 2024). *Fusicolla violacea* J-1 has 66.1% antifungal activity against *A. alternata*, suppressing mycelial growth and conidia germination, damaging cell membranes, increasing chitinase and β-1,3-glucanase activities, and targeting five other pathogens (Li et al. 2021). Although promising, biological methods can be further enhanced by incorporating plant-derived compounds. Natural extracts offer another layer of defense, often working in synergy with microbial agents.

3.4. Plant Extracts and Natural Products

Natural products and essential oils contain powerful antifungal compounds that offer organic alternatives to synthetic fungicides (Matrose et al. 2021). They can be used according to organic and integrated production systems. Plant extract natural compounds were also discovered to have potential application as fungistatic agents (Matrose et al. 2021; Pandey & Pant 2023). Plant extracts and natural products provide organic alternatives to synthetic fungicides. Phenolics, alkaloids, and essential oils are bioactive molecules with antifungal activity. For instance, citral and cinnamaldehyde have synergistic action in inhibiting *Penicillium expansum* by inducing membrane disruption and the onset of oxidative stress (Wang et al. 2018). Induction of autophagy in the pathogen, ferric chloride ($FeCl3$), inhibits *Colletotrichum gloeosporioides* in citrus fruits (Wang et al. 2023). Microbial antagonists that are present in plant extracts may complement integrated disease management systems (Matrose et al. 2021).

Conversely, extracts of native plants like *Croton chichenensis* and cinnamon were found to be active against pathogens like *Botrytis cinerea* and *Diaporthe eres* (Moo-Koh et al. 2022). Leaf extracts of *Eruca vesicaria* containing glucosinolate were found to be potentially useful towards the management of Oomycota-associated decline syndromes of kiwifruit (Mian et al. 2023). Research finding that biocontrol bacterium *Pantoea endophytica* strain KBA19 inhibits kiwifruit canker disease by T6SS antibacterial activity and contact- dependent killing system via co-culture assays (Shao et al. 2024). Curcumin induces the generation of reactive oxygen species (ROS) and apoptosis in *B. cinerea* hyphae by an NADPH oxidase-dependent mechanism (Hua et al. 2019).

Other disease control methods of strawberries are researched in some studies with the help of thyme, juniper, and essential oils. Essential oils were found to be quite effective in reducing grey mold by 50%, and thyme oil and juniper oil were also effective fungicides. Thyme oil and chitosan oil reduced powdery mildew by 84%-92%. Pre-flowering oil application reduced B. cinerea incidence (Soppelsa et al. 2024).

3.5. Physical and Other Alternatives

Despite all the control and prevention, there are still occasions where more precise or mechanical action is needed. Physical controls such as heat treatments, UV irradiation, and nanotechnology-based coating offer new, chemical-free techniques of postharvest disease control. They enhance shelf life and safety with fewer residue problems. Physical therapies, including heat therapy, ultraviolet, and ozone treatment, are increasingly under investigation as a non-toxic, sustainable way of managing fungal diseases.

The various studies have demonstrated that ferric chloride and magnesium oxide nanoparticles have been shown for the suppress of the growth of fungi and toxin production in pathogens such as *Aspergillus flavus* (Hussein &Al-Wahab 2020). Likewise, the physical techniques are of special worth for the kiwifruit, where problems of the chemical residue commonly limit fungicide use.

In this context, numerous physical methods of treatment, including curing, essential oils, gamma irradiation, heat treatment, ultraviolet light, and ozone treatment, are being explored as alternatives to chemical control (Yaşa et al. 2018). According to Yu et al. (2024), the pullulan treatment is highly effective against the soft rot caused by *Diaporthe nobilis* infection in kiwifruit. Furthermore, the citral-cinnamaldehyde mixture was also found to possess antifungal activity against *Penicillium expansum* (Wang et al. 2018), which used to work to inhibit the plasma membrane of the pathogen and cause oxidative stress (Wang et al. 2018). Likewise, the application of GRAS salts such as sodium metabisulfite (SMB) has been demonstrated in growth inhibition of the mycelia of certain fungal pathogens (Allagui & Ben Amara 2024), but phytotoxicity must be well controlled at the higher concentrations (Allagui & Ben Amara 2024). Likewise, *Eruca vesicaria subsp. sativa* leaf extracts and glucosinolates were discovered to possess inhibitory activity against *Oomycota* species causing Kiwifruit Vine Decline Syndrome (Mian et al. 2023).

Various physical treatments, including the heat shock, and fumigation with ozone have also been found effective for reducing the incidence of disease without damaging fruit quality (Luo et al. 2019; Ge et al. 2020). Likewise various emerging nanotechnology-based techniques, including nanocomposite packaging and nano-coatings, have been promising in inhibiting fungal growth and extending shelf life (Hu et al. 2011; Nepal et al. 2025b). Hexanal-based Enhanced Freshness Formulation (EFF) treatment effectively diminished mycelial growth of *B. cinerea*, suppressed spore germination, and enhanced defense-related enzyme activities in treated fruit, making it a good alternative fungicide to synthetic ones (Mthembu et al. 2025). Apart from treatments, postharvest precooling is also applicable, highlighting its benefits in loss minimization and enhanced produce quality, emphasizing the appropriate selection of technology (Subedi et al. 2022).

Nanotechnology offers novel opportunities and means of enhancing the management of abiotic and biotic stress so that there can be sustainable agriculture and food safety (Lowry et al. 2019). Engineered nanomaterials possess a size of less than 100 nanometers, which makes them pass through biological barriers. Hence, nanotechnology is enhancing conventional methods of crop nutrition and protection (Kah et al. 2019). Nanomaterials have also been used to improve kiwifruit quality by creating packaging arrangements that prevent fruit spoilage and preserve quality during storage. These arrangements inhibit *B. cinerea* spore germination, increase antioxidant content, and slow down ripening (Hu et al. 2011). However, their use in kiwifruit production and post-harvest disease management remains limited. Nanofertilizers, nanopesticides, and nano-biosensors are the research areas in the future to combat pathogen invasion and to activate defense mechanisms (Meng et al. 2014; Sarfraz et al. 2020). 'CuiXiang' kiwifruit black spot disease, when researched, also identifies potential pathogens such as *Alternaria* and *Cladosporium* species and entails analyzing transcriptomes for decision-making in preventative and treatment plans (Yang et al. 2021). Biologicals and cultural methods work best when combined with these technologies. Integrated Disease Management delivers a holistic method of consolidating all the techniques for optimal effectiveness.

3.6. Integrated Disease Management (IDM)

IDM engages various prevention approaches into a single, unified management strategy. IDM is contextually flexible since it tries to balance effectiveness, expense, and ecology. Integrated Disease Management (IDM) entails the utilization of various methods with the perspective to achieve sustainable suppression of diseases. IDM reduces reliance on chemical fungicides through cultural, biological, chemical, and natural approaches as it maximizes overall efficiency (Sommer et al. 1983; Kim & Koh 2018).

For kiwifruit, IDM practices encompass orchard hygiene, use of biocontrol agents like *Trichoderma* spp., and incorporation of natural extracts for pathogen suppression. Solarization and biofumigation have also been effective in the control of soilborne pathogens in kiwifruit plantations. A combination of these with molecular diagnostics results in early detection and intervention, limiting crop loss and environmental impact (Sui et al. 2021). IDM is no utopian concept; it is a practical necessity for sustainable horticulture.

Prevention is the connecting thread between early diagnosis and long-term disease control. Through a range of options suitably tailored to specific crops and situations, particularly kiwifruit systems, producers can achieve significant losses and environmental load reductions.

4. Outcomes, Challenges, and Future Directions

In recent postharvest fungal disease management studies on fruits, various possible outcomes were unveiled. For apple, biological control agents (BCAs) appeared as environmentally friendly and effective postharvest decay management alternatives with ongoing investigations on the pathogenesis of major decay fungi and recovery of bacterial and fungal antagonists. Additive application and physical treatment to increase the activity of BCAs, as well as future development of antimicrobial consortia and novel antimicrobial molecules, are in the pipeline (Leng et al. 2023). In bananas, essential oils from *Syzygium aromaticum* and *Mentha piperita* have shown significant antifungal activity, with a level of up to 100% inhibition of fungal growth, suggesting their applicability as green management strategies (Pawar et al. 2024). Advances in the molecular mechanisms of postharvest fungal pathogenicity have revealed essential pathogenic genes and regulatory pathways, and provided a theoretical basis for new control technologies (Zhang et al. 2021). Integrated strategies are emphasized for managing postharvest diseases on various fruits and vegetables with a view to reducing qualitative and quantitative losses during storage (Rahul et al. 2015). Further, RNA interference (RNAi)-mediated fungicides, particularly spray-induced gene silencing (SIGS), have been emphasized as an emerging alternative to conventional chemical fungicides with a safer and technologically advanced strategy for postharvest spoilage management (de Oliveira Filho et al. 2021). These studies collectively underscore the importance of combined and innovative measures towards enhancing the shelf life and fruit quality during and following harvest.

Despite strong advances in detection and prevention, gaps remain between innovation and application. Key challenges include:

- **Development of Resistance**: Chemical fungicides overuse has led to resistance in pathogens like *Botrytis cinerea*, necessitating the development of alternative strategies (Jørgensen & Heick 2021).
- **Detection Limitations:** While molecular and non-destructive methods are advanced, their high costs and technical requirements often limit adoption in resource-poor conditions (Romero-Cuadrado et al. 2024).
- **Climate Change:** Shifting climatic conditions are worsening fungal disease occurrence and severity, underscoring the need for adaptive management strategies (Xu et al. 2022).

- **Technological Integration and Adoption Barriers:** Technology is transforming plant disease management from AI-powered diagnostics to smartphone-based sensors. However, practical constraints such as cost, training, and infrastructure often slow their adoption.

Preserving indigenous knowledge is a very important factor in identifying the disease in smallholders' farms and storage (Nepal et al. 2025a). To minimize the incidence and spread of disease in the future, farmers need to practice organic fruit farming because the market demand for organic produce is high and fruits will not remain for long in storage (Rai et al. 2025b). The way forward for research has to emphasize the development of low-cost, field-deployable detection systems, enhancement of biocontrol agent delivery systems, and the quest for genetic markers for disease resistance. Genome editing technologies such as CRISPR-Cas9 can be used to develop resistant cultivars, which will further integrate disease management (Gebremichael et al. 2021; Degnan et al. 2023). The application of CRISPR in other fruits, such as bananas, is intended to increase resistance to devastating fungal pathogens, reflecting its broad use in sustainable agriculture through the knockout of the susceptible genes from fruits (Dixit and Upadhyay 2022). Overall, these advancements are reflective of the role of CRISPR in driving a revolution in the control of fruit disease through precision genetic editing (Morio et al. 2020). Besides, field trials need to be carried out to validate the effectiveness of potential preventive treatments under field conditions (Fedorchenko et al. 2024). Various studies on the genetic mechanism of disease resistance in kiwifruit and whether genetic transformation or breeding programs can be carried out to make it more resistant are other areas of future study (Li et al. 2020; Wang et al. 2020). Finally, the knowledge about the effect of cultivation management on kiwifruit microbiome and its disease suppression function must be carried out for further validation of the findings (Sui et al. 2021). Furthermore, the genome of *Pestalotiopsis microspora* was characterized and sequenced, which contains 14,711 predicted genes, 870 putative CAZy genes, 845 transcription factors, 86 secondary metabolism gene clusters, 28 effectors, 109 virulence-enhanced factors, and seven counties (Deng et al. 2024). This provides potential doors for gene study in the future on diseases in Kiwifruit.

The integration of AI with handheld real-time sensors and non-destructive imaging has encouraging ways of detecting post-harvest fungal diseases of fruits in early stages. For example, the use of CNN and YOLO-V2 has proven useful to detect fungal infection in *Phyllanthus Emblica* at high accuracy rates to facilitate timely treatment using eco-friendly practices. Furthermore, optical technologies, including RGB imaging and hyperspectral sensors, make automatic disease detection possible to boon precision agriculture (Mahlein 2016). Smartphone-based systems have even been proposed to make it possible for growers to detect apple scab with a mean average precision of 70%, thereby aiding integrated pest management plans (Yang et al. 2023). Apart from this, a machine learning-based portable electronic nose has also been shown to be precise (94.4-96.8%) in detecting *Fusarium oxysporum* in tomatoes, which suggests the possibility of real-time monitoring of the level of the pathogen (Feng et al. 2022). Last but not least, label-free Raman microspectroscopic imaging has also been shown to be 100% precise in the early detection of apple ring rot classification, which suggests the application of non-destructive methods in the management of diseases in fruits (Li et al. 2024).

Detection and prevention issues of horticultural crops are utilizing rapid-diagnostic methods, fungicide resistance, and new technologies, necessitating new approaches like nanotechnology-based handheld biosensors (Shukla et al. 2023). An understanding of plant defense mechanisms is necessary to create an effective resistance against fungal pathogens, and digital technology like convolutional neural networks can potentially provide automated detection of diseases (Xu et al. 2022; Fedorchenko et al. 2024). The precision agriculture equipment such as molecular biology and imaging methods, can enhance early detection and sustainable management techniques, reducing chemical treatment dependency (Traversari et al. 2021). There is significant role of microbiome in fruits as well, utilizing Shotgun metagenomic sequencing to provide valuable insights into these functions (Wu et al. 2019). Further research is needed to comprehend fruit microbiota and its potential role in managing postharvest diseases (Wu et al. 2019). Post-harvest conditions of fruits like shelf life and incidence of fungal disease also depend on pre-harvest and harvest conditions, so proper management of pests (monkeys, squirrel, etc.) plays vital role as they can cause mechanical damage and trigger diseases (Rai & Rai 2024c). Nowadays, agro ecological aspects of farming system deserves prime importance from the context of food sustainability, promotion of social justice, and environment protection (Chaudhary et al. 2023) there by development of climate resilient farming system of the particular locality
Some of the future directions for detection system can be:

Portable Biosensors: Nano-enabled biosensors with smartphone interfaces for rapid in-field detection (Fedorchenko et al. 2024).

Artificial Intelligence Integration: Use of CNNs and machine learning for image-based disease detection (Shukla et al. 2023).

CRISPR-based Diagnostics: Potential for extremely fast and accurate detection (Gebremichael et al. 2021**)**.

Metagenomics Expansion: It is for the understanding of whole microbiomes to predict pathogens (Wu et al. 2019).

Precision Agriculture: It is helpful for them to integrate detection tools with GPS and data analytics for targeted interventions (Traversari et al. 2021).

Field-Deployable Kits: In the future, the application of compact qPCR and LAMP kits with solar-powered systems (Park et al. 2023).

5. CONCLUSION

Various fungal pathogens are the main reason for severe concern in worldwide horticultural yields of fruits and vegetables, and kiwifruit is also vulnerable to postharvest disease like rot. The simple detection methods have been replaced by advanced molecular and non-destructive methods with better accuracy and effectiveness. Various cultural practices, biological control, and ecologically friendly technologies have become successful alternatives to conventional chemical use. The appropriate combination and judicious application of these approaches through an Integrated Disease Management (IDM) system can reduce crop production loss with minimal environmental hazard. Fungicide resistance, global climate change, and access to high technologies are some of the issues where research and technological development on a day-to-day basis are necessary. Future research needs to focus on field-deployable diagnostic kits, nanotechnology and gene editing applications towards pathogen-resistant crop lines, and investigation of the fruit microbiome in inhibiting pathogens. Long-term assistance to the horticulture industry will be founded on collaborative and multi-disciplinary interventions.

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