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INNOVATIVE STRATEGIES FOR POST-HARVEST DISEASE MANAGEMENT IN FRUIT CROPS: A REVIEW

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ABSTRACT

Postharvest diseases significantly impact the quality and marketability of fruit crops, leading to substantial economic losses. The primary causative agents include fungal pathogens such as *Botrytis cinerea*, *Colletotrichum gloeosporioides*, and *Penicillium expansum*, which cause gray mold, anthracnose and blue mold, respectively. Infection can occur before, during, or after harvest, exacerbated by environmental factors, mechanical injuries, and improper handling. Traditional management strategies rely on synthetic fungicides, but concerns over chemical residues and environmental impact have led to increasing interest in alternative control methods. Promising approaches include physical treatments (cold storage, heat treatment, and ultraviolet-C light), biological control using antagonistic microorganisms, and novel chemical treatments such as methyl thujate and nitric oxide. Recent advances in nanotechnology and modified atmosphere packaging also offer innovative solutions to extend fruit shelf life and reduce postharvest losses. This review highlights the major postharvest pathogens, their modes of infection, and emerging sustainable strategies for disease management to enhance food security and minimize losses in horticultural production.
***Keywords*:** Post-harvest, Botrytis, Methyl thujate, Management, Nitric oxide, Penicillium

Introduction

The increasing global population necessitates a corresponding increase in food production to meet the growing demands. It is estimated that global crop production needs to double by 2050; however, current estimates indicate a significant shortfall, primarily due to crop loss. Plant diseases, insects, and weeds are responsible for a global crop production decrease of approximately 36%, with plant diseases alone reducing crop yields by 14% (Dongchao *et al*., 2018; Ray *et al*., 2013). Postharvest losses significantly impact the availability of fruits and vegetables. For instance, it is estimated that about 20-25% of harvested fruits decay due to filamentous fungi during postharvest handling, even in developed countries, making the control of fungal infections critical at this stage (Kitinoja & Kader, 2015). In citrus fruits, postharvest pathogens are responsible for nearly 50% of the wastage occurring at various storage of fruits after harvest (Meijiao *et al*., 2014). Pathogenic fungi, such as *Botrytis cinerea*, which causes gray mold, lead to severe economic losses by affecting over two hundred plant species worldwide (Dongchao *et al*., 2018). Currently, the control measures for phytopathogens during pre- and post-harvest practices rely heavily on synthetic chemicals. However, the use of these chemicals is becoming increasingly problematic due to stricter legislation and growing public concern about their toxicological risks to human health (Meijiao *et al*., 2014; Scortichini, 2022). Consequently, there is a growing interest in physical treatments to control many postharvest diseases in fruits, owing to their total absence of residues in the treated products and minimal environmental impact (Dongchao *et al*., 2018). One promising alternative is the use of methyl thujate, a monoterpenoid substance, which has been effective in controlling postharvest gray mold caused by *B. cinerea* on apple fruit (Dongchao *et al*., 2018; Ma *et al*., 2020).

Methyl thujate has shown strong inhibitory effects on spore germination, germ tube elongation, and mycelial spreading of *B. cinerea* (Meijiao *et al.*, 2014). Additionally, nitric oxide (NO) treatment has proven to delay flesh softening, yellowing, and changes in soluble solids content (SSC) and titratable acidity (TA), as well as peaks of respiration rate and ethylene production during ripening (Meijiao *et al.*, 2014; Liu *et al.*, 2023). The resistance of NO-treated mangoes to anthracnose may be attributed to the activation of defence responses and delayed ripening (Meijiao *et al.*, 2014). In light of these developments, the identification and development of unexplored chemicals as potential antifungal compounds have become urgent to meet consumer requirements for food security. The induction of natural disease resistance (NDR) in harvested horticultural crops using physical, biological and chemical elicitors has received increasing attention in recent years, being considered a preferred strategy for disease management (Dongchao *et al.*, 2018; Xu *et al.*, 2022).

Common Causal Organisms of Post-Harvest Diseases

Botrytis cinerea causes gray mold rot in a wide range of fruits and vegetables, including grapes, strawberries, and tomatoes. Thriving in cool, humid conditions, it leads to significant losses during storage and transport (Williamson *et al.*, 2007). *Colletotrichum gloeosporioides*, the causal agent of anthracnose, affects tropical and subtropical fruits such as mango, papaya, and guava, resulting in dark, sunken lesions that render the fruit unmarketable (Dean *et al.*, 2012). *Penicillium expansum*, responsible for blue mold rot, primarily infects apples and pears, producing blue-green spores on the fruit surface and causing substantial post-harvest losses (Tian *et al.*, 2016). In addition to these, several other pathogens contribute to various post-harvest diseases in fruit crops (Table 1).

Table 1 : Post harvest diseases of major fruit crops.

Crop	Disease	Causal organism
Mango	Anthracnose	*Colletotrichum gloeosporioides* Penz
	Stem end rot	*Phomopsis mangifera*
	Black mold	*Aspergillus niger* Teigham
	Alternaria rot	*Alternaria alternate* Keissi
	Gray mold	*Botrytis cineria* Pers
	Blue mold	*Penicillium expansum* Link
Banana	Crown rot	*Fusarium* spp Mason
	Black rot	*Nigrospora spharica* Mason
	Ceratocystis fruit rot	*Thielaviopsis paradoxa* Dade
Grapes	Gray mold	*Botrytis cinerea* Pers
Citrus	Blue mould	*Penicillium expansum* Link
	Green mould	*Penicillium digitatum*
	Black centre rot	*Alternaria citri*
	Stem end rot	*Phomopsis citri*
Pome fruits	Grey mould	*Botrytis cinerea*
	Bitter rot	*Colletrotrichum gloeosporioides*
	Alternaria rot	*Alternaria spp.*
Stone fruits	Brown rot	*Monilia spp.*
	Grey mold	*Botrytis cinerea* Pers
	Blue mold	*Penicillium spp*

Mode of Infection

Infection of fruit by postharvest pathogens can take place at various stages, including before, during, or after harvest. Among these, infections occurring before harvest that remain dormant until the fruit ripens are particularly prevalent in tropical fruit crops. Anthracnose, a significant postharvest disease, affects a wide range of tropical and subtropical fruits such as mango, banana, papaya, and avocado. This disease arises from quiescent infections established prior to harvest and is caused by various species of *Colletotrichum* (Prusky *et al.*, 2000).

Infection can also occur during and after harvest through wounds created when the fruit is severed from the plant. For instance, banana crown rot results from pathogens entering through such wounds (Griesbach, 2003). Additionally, late-season infections can lead to postharvest diseases, such as brown rot of peach (*Monilinia fructicola*) and gray mold of grape (*Botrytis cinerea*) (Janisiewicz and Korsten, 2002).

Mechanical injuries, including cuts, abrasions, pressure damage, and impact damage, frequently occur during harvesting and handling. These injuries further facilitate the entry and proliferation of postharvest pathogens, exacerbating disease development (Eckert & Ogawa, 1988). Proper management practices during preharvest, harvesting, and postharvest stages are essential to minimize infections and maintain fruit quality.

Impact of Pre-Harvest Conditions on Post-Harvest Disease Development

Weather plays a critical role in plant diseases by affecting the survival of inoculum and the persistence of pesticide residues on crops at harvest (Fig. 1). A high inoculum load and favourable infection conditions during the growing season often led to severe infections by the time the produce is harvested. For instance, conidia of the fungus responsible for bull's-eye rot are rain-dispersed from cankers and infected bark to fruit, particularly when prolonged rainfall occurs near harvest, resulting in fruit decay during cold storage (Spotts *et al.*, 2009). The physiological condition of produce at harvest also determines its safe storage duration. For example, apples are harvested slightly immature to extend their storage life. As fruits undergo ripening and senescence, they become more susceptible to pathogen infections. However, proper crop nutrition management can enhance fruit resistance to decay (Kader, 2002). Additionally, physical injuries compromise the fruit's natural defense by rupturing the exocarp (outer protective layer), creating entry points for pathogens. Damage caused by animals, birds, or human activities during cultural practices and harvest further increases the risk of infection (Prusky & Lichter, 2007).

Post-Harvest Factors Contributing to Decay

Improper handling of fruits leads to bruises, cracks, and softening of the fruit surface, creating entry points for pathogen infection (Fig 1). Proper care after harvest is essential to protect commodities from decay-causing organisms (Kitinoja & Kader, 2002). Maintaining sanitation in packing areas is equally crucial, as organic matter such as culls, extraneous plant parts, and soil can serve as substrates for pathogenic growth, increasing the risk of post-harvest decay (Sivakumar & Bautista-Baños, 2014).

Management Strategies for Post-Harvest Diseases

Effective management of post-harvest diseases is crucial to maintaining the quality and marketability of fruit crops. Various strategies have been developed to control these diseases, including the use of chemical, biological, and physical methods. These approaches aim to minimize losses during storage, transportation, and marketing while ensuring food safety and environmental sustainability. Let's dive into some key management strategies to combat post-harvest diseases in fruit crops.

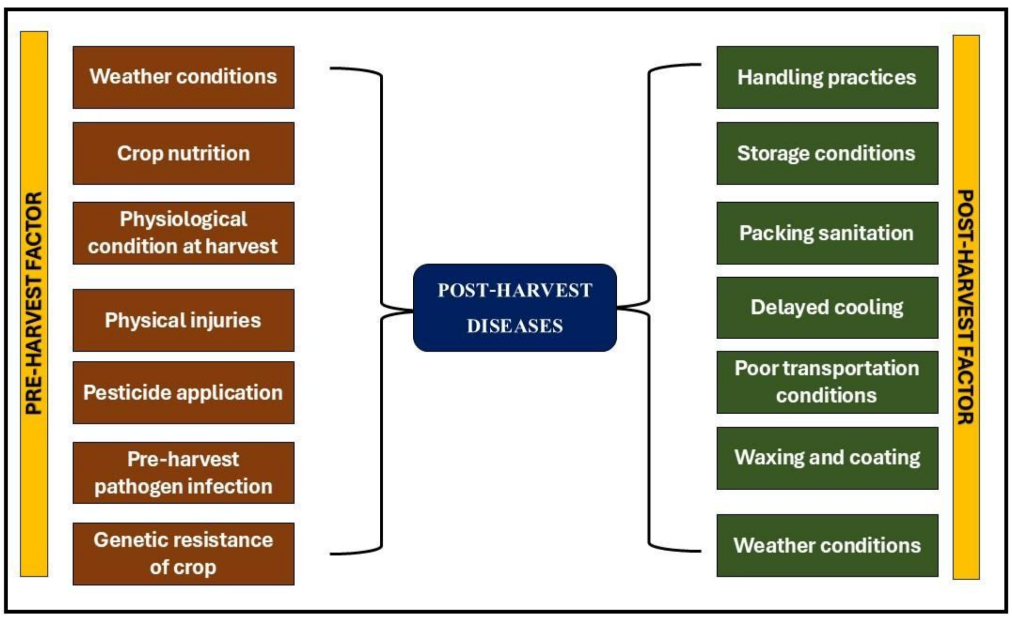

Fig. 1 : Pre-harvest and Post harvest factor influencing post-harvest diseases

Cold storage

The deterioration of fruits and vegetables depends on temperature, respiration rate, and stress from harvesting and postharvest handling. Lowering the temperature of the product as quickly as possible after harvest helps maintain high quality and attractiveness for customers (Kader, 2002). Low temperatures exert their effect both indirectly and directly. Indirectly, they reduce the metabolism of the host, delay senescence, and help maintain fruit resistance to fungal infection (Mattheis & Fellman, 1999). Directly, they inhibit or delay the growth and enzymatic activity of pathogens, thereby reducing post-harvest decay (Snowdon, 1990). Moreover, low temperature prevents moisture loss from host tissues and consequent shrivelling, which allows tissues to maintain a high level of resistance to pathogens compared to fruit kept in low moisture environments (Ippolito *et al.*, 1994). Important postharvest fungal pathogens exhibit varying temperature thresholds for growth inhibition. Certain fungi cease growth at temperatures well above 0°C, such as *Aspergillus niger* at 11°C, *Colletotrichum gloeosporioides*, and *Colletotrichum musae* at 9°C (Sommer, 1985). Cold storage at 0°±1°C effectively arrests the growth of these fungi, thereby preventing disease development. However, other fungal species can grow at much lower temperatures, including *Cladosporium herbarum* at -4°C, *Alternaria alternata* at -3°C, *Penicillium expansum* at -3°C, and *Botrytis cinerea* at -2°C (Sommer, 1985). Understanding the temperature tolerance of different fungal pathogens is essential for developing effective postharvest storage strategies.

Heat treatment

a. (a) Hot Air Treatment/Curing:

The exposure of fruits to an air atmosphere heated to temperatures higher than 30°C at high relative humidity (RH > 90%) for several hours or days is known as hot air treatment or curing. This method is effective in controlling postharvest diseases. A curing treatment at 33°C for 65 hours effectively controlled both green and blue mold, caused by *Penicillium digitatum* and *Penicillium italicum*, respectively, on oranges and lemons (Plaza *et al*., 2003; Plaza *et al*., 2004b). An intermittent curing treatment of two cycles of 18 hours at 38°C completely controlled *P. italicum* on mandarins stored under ambient conditions (Perez *et al*., 2005). Additionally, curing at higher temperatures, 40°C, reduced treatment time to 18 hours for controlling both *P. digitatum* and *P. italicum* on oranges (Nunes *et al*., 2007).

b. (b) Hot water treatment

Hot water treatment (HWT) is a non-conventional approach to control postharvest decay using water at temperatures above 40°C. HWT has been have been widely used in fruit Crops for controlling postharvest fungal pathogens (Table 2). This method provides more efficient heat transfer than air, requiring shorter treatment times compared to hot air treatments. Additionally, HWT is cost-effective compared to other heat treatments (Jacobi *et al*., 2001). HWT is typically applied by completely immersing the commodity in hot water, known as a hot water dip (HWD), or by using a hot water rinse brushing (HWRB) method (Fallik, 2004). Studies have shown that hot water treatment (HWT) failed to control *Penicillium digitatum* and *P. expansum* diseases in citrus (Porat *et al*., 2000).

Improper hot water treatments can cause significant damage to horticultural crops (Table 3). These damages include skin browning, surface pitting, rind black spots, stem browning, flesh darkening, water loss, and fails to ripen normally (Lurie, 2008). For instance, excessive temperatures or prolonged exposure can lead to skin browning in apples, failure to soften in bananas (Reyes *et al*., 1998), and rind browning in melons (Sivakumar and Fallik, 2013).

Table 2 : Hot Water Treatments for Disease Control in Horticultural Crops

Commodity	Pathogen Target	Disease	HWT	Source
Apple	*Botryosphaeria dothidea*	White rot	HWRB: 55°C 30s	Oster *et al*., 2006
Apple	*Penicillium expansum*	Blue mold	HWRB: 55°C 15s	Fallik *et al*., 2001
Apple	*Neofabraea vagabunda* (syn. *N. alba*); *P. expansum*	Bull's eye rot, blue mold	HWD: 45°C 10 min	Neri *et al*., 2009; Spadoni *et al*., 2015a
Banana	*Chalara paradoxa*; natural infections	Crown rot	HWD: 45°C 20 min; 50°C 10-20 min	Reyes *et al*., 1998; Alvindia, 2012
Grapefruit	Natural infection; *P. digitatum*	Green mold	HWD: 53°C 3 min; HWRB: 56°C 20s	Rodov *et al*., 1995; Porat *et al*., 2000
Kiwifruit	*Botrytis cinerea*	Gray mold	HWD: 46°C 15 min; 48°C 8 min	Cheah *et al*., 1992
Lemon	*P. digitatum*	Green mold	HWD: 52-53°C 2 min; HWRB: 63°C 15s	Nafussi *et al*., 2001; Smilanick *et al*., 2003
Mango	*Colletotrichum gloeosporioides, Lasiodiplodia theobromae, Alternaria alternata*	Anthracnose, stem-end rot, black spot disease	HWD: 53°C 20 min; 55°C 5 min; HWRB: 56-64°C 15-20s	Prusky *et al*., 1999; Alvindia and Acda, 2015; Sripong *et al*., 2015
Nectarine & Peach	*Monilinia fructicola, M. fructigena, M. laxa*	Brown rot	HWD: 60°C 30-60s	Karabulut *et al*., 2010; Spadoni *et al*., 2013, 2014
Orange	*P. digitatum, P. italicum*	Green mold, blue mold	HWD: 50-53°C 2-3 min; 56°C 20s; HWRB: 56°C 20s; 63°C 15s	Schirra *et al*., 1997; Porat *et al*., 2000; Palou *et al*., 2001; Smilanick *et al*., 2003; Strano *et al*., 2014
Papaya	*C. gloeosporioides*	Anthracnose	HWD: 48°C 20 min; 54°C 3-4 min	Couey and Alvarez, 1984; Li *et al*., 2012

Pear	*P. expansum*	Blue mold	HWD: 46°C 15 min	Zhang *et al*., 2008
Plum	*M. fructicola*; natural infections	Brown rot	HWD: 45°C 35 min; 50°C 30 min; 60°C 60s	Abu-Kpawoh *et al*., 2002; Karabulut *et al*., 2010
Strawberry	*B. cinerea, Rhizopus stolonifer*	Gray mold, soft rot	HWD: 55-60°C 30s	Karabulut *et al*., 2004
Tangerine	*P. digitatum*	Green mold	HWRB: 56°C 20s	Porat *et al*., 2000

HWRB: Hot water rinse brushing; **HWD**: hot water dip

Table 3: Adverse Effects of Improper Hot Water Treatments on Horticultural Crops

Commodity	Treatment	Possible Damage	Source
Apple	50–56°C 3–4 min; 55–65°C 15–30s	Skin browning; decay increase	Fallik *et al*., 2001; Bompeix and Coureau, 2007; Maxin *et al*., 2012
Banana	45°C 40 min; 50°C 20 min; 55°C 10 min	Skin browning, failure to soften	Reyes *et al*., 1998; Alvindia, 2012
Kiwifruit	48°C 15 min	Premature ripening, decay increase	Cheah *et al*., 1992
Mango	42–48°C 30–120 min	Skin scalding/yellowing, darkened lenticels, cavitation	Jacobi *et al*., 2001
Nectarine, Peach, Plum	65°C 30s	Surface injury	Karabulut *et al*., 2010
Orange	53–55°C 2.5–3 min; 60°C 20s	Rind browning; surface injury	Schirra *et al*., 1997; Porat *et al*., 2000; Palou *et al*., 2001
Strawberry	45°C 15 min	Shrivel, loss of shine	Wszelaki and Mitcham, 2003

Ultraviolet-C light

Among physical treatments, ultraviolet-C light (UV-C, 190–280 nm) has shown promising applications due to its direct antimicrobial activity and the induction of resistance in the host (Romanazzi *et al*., 2016). UV-C light effectively reduced both the number of infected fruits and the lesion diameter of *Botrytis cinerea* on kiwifruit and table grapes that were artificially inoculated with the pathogen after UV-C illumination (Nigro *et al*., 1998a, 1998b). Additionally, low doses of UV-C were effective in reducing postharvest diseases in grapefruit (Droby *et al*., 1993) and strawberries (Nigro *et al*., 2000). UV-C light effectively reduced both the number of infected fruits and the lesion diameter of *Penicillium expansum* on apples and pears that were artificially inoculated with the pathogen after UV-C illumination (Syamaladevi *et al*., 2015). Additionally, low doses of UV-C were effective in reducing postharvest diseases in mangoes (Terao *et al*., 2015) and tomatoes (Turtoi, 2013).

Controlled atmosphere and modified atmosphere

Controlled atmosphere (CA) and modified atmosphere (MA) techniques involve altering the atmospheric gas composition from normal levels, typically by increasing carbon dioxide (CO_2) levels, reducing oxygen (O_2) tension, or both (Thompson, 2010). Studies have demonstrated that CA, in comparison to normal air storage, can effectively reduce post-harvest decay caused by *Rolstonia stolonifera, Cladosporium herbarum,* and *Penicillium expansum* in apples (Nilsson *et al*., 1956). Additionally, CA storage has been shown to inhibit the growth of *Botrytis cinerea* in strawberries (Smith *et al*., 1999) and control the development of *Alternaria* rot in tomatoes (Jones *et al*., 2001). Similarly, MA packaging has been effective in reducing decay caused by *Aspergillus niger* in figs (Petracek *et al*., 2002) and *Rhizopus stolonifer* in peaches (Kader *et al*., 2003).

Chemical treatment

Chemical treatments remain a primary strategy for controlling post-harvest diseases in fruit crops due to their cost-effectiveness, ease of application, and dual curative and preventive actions against infections. However, the increasing concerns of consumers and regulatory bodies regarding human health and environmental impact have led to a more cautious approach to fungicide use (Thompson, 2010). Examples of commonly used chemical treatments include Imazalil, which is effective against green mold (*Penicillium digitatum*) and blue mold (*Penicillium italicum*) in citrus fruits (Eckert & Ogawa, 1988). Thiabendazole is often used to manage blue mold and gray mold (*Botrytis cinerea*) in apples and pears, providing both preventive and curative actions (Tian *et al*., 2002). Fludioxonil is applied to control several post-harvest diseases, including gray mold in strawberries and kiwifruit, and *Penicillium spp.* in citrus fruits (Smilanick *et al*., 2008). Pyrimethanil is used for controlling *Botrytis cinerea* in grapes and other fruits, offering both preventive and curative effects (Neri *et al*., 2006). Prochloraz is effective against anthracnose (*Colletotrichum gloeosporioides*) in mangoes, reducing decay and maintaining fruit quality during storage (Johnson *et al*., 1992). Recent advances in post-harvest disease management emphasize the need for safer and more sustainable alternatives to synthetic fungicides (Moradinezhad & Ranjbar, 2023). Various methods of chemical treatments have been employed to control postharvest fungal pathogens in fruit commodities. Table 4 presents a summary of selected chemical treatment methods, highlighting their effectiveness against specific pathogens and commodities. These treatments play a crucial role in reducing postharvest disease incidence and extending the shelf life of fruits. The application of chemical treatments is often tailored to the target pathogen, fruit type, and environmental conditions to ensure optimal disease management and minimize potential adverse effects.

Table 4: Methods of Chemical Treatments for Post-Harvest Disease Management

Treatment	Delivery System	Sources	Activity	Advantages	Disadvantages
Chlorine	Water	Gas or liquid (Cl_2 or NaOCl)	Fruit surface/In solution	Inexpensive, effective at low rates	Sensitive to pH and organic load; corrosive; reactive
Chlorine dioxide	Water	On-site generation	Fruit surface/In solution	Less sensitive to organic load	Initial cost of equipment; corrosive; training
Ozone	Water (low solubility)/ Air	On-site generation	In solution, but poor solubility; Air: anti-sporulation	Non-chlorine based, no disposal issues	Poor water solubility, initial cost of equipment; corrosive; training
Acidified hydrogen peroxide	Water	Liquid (H_2O_2)	Fruit surface/In solution; some wound activity	Less sensitive to organic load and pH, no disposal issues	Conc. limits, cost, some sensitivity to Cl, pH, and organic load
Postharvest fungicide (e.g., Scholar)	Water	Dry or liquid formulation	Wound protection	Highly effective	Residues; safety concerns; export tolerances (MRLs)

Biological method

Biological methods for postharvest disease management in fruits involve the use of antagonistic microorganisms (Table 5). Promising agents include *Metschnikowia fructicola, Candida oleophila, Aureobasidium pullulans, Bacillus subtilis, Ulocladium, and Sporidiobolus pararoseus*. These microorganisms have demonstrated effective control of postharvest diseases (Sharma *et al*., 2009).

Table 5: Antagonistic microorganisms for controlling post-harvest pathogens in fruits

Antagonist	Disease (Pathogen)	fruit
Acremonium brevae	Grey mould *(Botrytis cinerea)*	Apple
	Botrytis rot *(Botrytis cinerea)*	Grape
Candida sp	Anthracnose *(Colletotrichum gleosporioides)*	Mango, Papaya
	Penicillium rot *(Penicillium digitatum, P italicum)*	Citrus
Psuedomonas sp	Brown rot *(Monilia laxa)*	Peach
Trichoderma sp	Anthracnose *(Colletotrichum gleosporioides)*	Mango, Papaya
	Stem end rot *(Botryodiplodia theobromae)*	Rambhutan, Mango, Citrus

Recent Advances in Managing Post-Harvest Diseases

The traditional methods for managing post-harvest diseases have often proven to be insufficient in effectively controlling the spread of pathogens. This has led to the development of innovative techniques aimed at enhancing disease management. Recent advances in this area include the use of Methyl Thujate, which inhibits the growth of various pathogens and Oligo-Chitosan sprays, which enhance the natural defence mechanisms of fruits and vegetables (Kader, 2002). Nitric oxide treatments delay the ripening process and enhance resistance to microbial infections (Mattheis & Fellman, 1999). Nano packaging extends the shelf life of produce by providing an antimicrobial environment (Snowdon, 1990). The discovery of new biocontrol agents and microbe-based bio-control products offers environmentally friendly disease management solutions. These advancements represent a significant step forward in reducing post-harvest losses and ensuring the quality and safety of fruits and vegetables.

Methyl Thujate

Methyl thujate, a monoterpenoid substance with natural preservation properties, is originally sourced from the heartwood of *Thuja plicata*. It is responsible for the unique aroma and also has minor pest repellent properties (Komaki *et al*., 2008; Okabe and Saito, 1994). Extensively used for protecting against environmental threats, purifying air, repelling insects, and producing essential oils (Clydesdale, 1997; Gonzalez, 2004), methyl thujate plays a significant role in various applications. Cedarwood oil alcohols and terpenes, including methyl thujate, are food additives considered by the US Food and Drug Administration (FDA) to be Generally Recognized as Safe (GRAS). These additives can be used as flavour enhancers, flavouring agents, or adjuvants (Clydesdale, 1997). Methyl thujate strongly inhibits spore germination, germ tube elongation, and mycelial spreading of *Botrytis cinerea* and other mold growth on fruits. Okabe and Saito (1994) reported that methyl thujate has minor pest repellent properties and is effective in reducing mold growth on various fruits, thereby extending their shelf life.

Oligo-Chitosan (OCH)

Oligo-Chitosan (OCH), derived from the partial hydrolysis of chitosan obtained from crab and shrimp shells, is a biodegradable, non-toxic, and biocompatible oligosaccharide widely used in agriculture. OCH acts as a plant disease vaccine, inducing plant defense responses against pathogens in crops like tobacco, wheat, rice, and grapevine (Yin *et al*., 2010; Aziz *et al*., 2006). Additionally, OCH directly inhibits the mycelial growth of fungi such as *Alternaria alternata*, *Monilinia fructicola*, and *Botrytis cinerea* (Yan *et al*., 2012). Recent studies highlight its effectiveness as a postharvest treatment for citrus, tomatoes, apples, and peaches, offering a promising eco-friendly alternative to synthetic fungicides (Yan *et al*., 2011).

Nitric oxide (NO)

Nitric oxide (NO), a highly reactive free radical gas, is recognized as a multifunctional signal molecule that participates in diverse physiological processes across various species (Shi *et al*., 2012). Postharvest application of NO, either through direct gas fumigation or via NO-releasing agents such as 3-morpholino sydnonimine, 2,2-(hydroxynitroso-hydrazine)-bisethanamine, and sodium nitroprusside (SNP), has been shown to delay fruit ripening and senescence, as well as enhance tolerance to chilling stress in a number of climacteric and non-climacteric fruits (Singh *et al*., 2013). Recent research has also focused on the effect of NO on postharvest diseases. Treatment of fruits with NO or its precursor (l-arginine) resulted in enhanced resistance against *Botrytis cinerea* and *Rhizopus stolonifer.* This treatment increased activities of defense-related enzymes and promoted reactive oxygen species (ROS) metabolism (Zheng *et al*., 2011). Additionally, NO signaling has been found to participate in systemic acquired resistance in fruits. For example, preharvest application of NO in mango reduced anthracnose infection (Hu *et al*., 2014).

Nano-Particles for Post-Harvest Disease Control

Nano-particles are emerging as a new trend for the prolonged storage of fruits and vegetables (Table 6). Research has shown that these nano-particles possess the ability to inhibit pathogen growth on fruits, thereby extending their shelf life and maintaining quality (Singh *et al*., 2013). Their application in post-harvest treatments offers a promising alternative to conventional methods, providing an innovative and effective approach to disease management in horticultural products (Mishra *et al*., 2020).

Table 6: Nanoparticles used for controlling post-harvest pathogen growth in fruit crops.

Crop	Nanoparticle	Use	Reference
Mango	Methylcellulose incorporated with Thai essential oils	Inhibit *C.gloeosporioides* and prolonged shelf-life	Klangmuanga and Sothornvit (2018)
Citrus	Essential oil with nano clay polyethylene films	Inhibited *Penicillium digitatum* and *P. italicum*	Yahyszadeh (2016)
Strawberry	Thermoplastic starch/clay nanocomposites	Antimicrobial synergy over *Botrytis cinerea*	Requena *et al.*, (2017)

New Biological Agents

New biological agents have been identified for the effective control of disease infections. These new strains and newly identified organisms have shown promising results in controlling various fungal pathogens, offering alternatives to traditional fungicides. Research has demonstrated that these biological agents (Table 7) can effectively manage diseases, reducing the reliance on chemical treatments and promoting sustainable agricultural practices.

Table 7: Effective biological agents for controlling post-harvest pathogens

Antagonist	Pathogen	Reference
Bacillus amyloliquefaciens BUZ-14	*Botrytis cinerea, Monilinia fructicola, M laxa, Penicillium digitatum, P expansum and P italicum*	H. Calvo *et al.*, 2017
Pichia caribbica	*Penicillium expansum*	Xu *et al*. (2013)
P guilliermondii	*Botrytis cinerea*	Zhang *et al*. (2013a)
Candida oleophila	*Penicillium digitatum, P. expansum*	Liu *et al*. (2011)

Microbe based products

In recent years, various natural compounds, organic and inorganic salts, in combination with antagonists, have been found to enhance the efficacy of most biocontrol agents. These combinations provide broad-spectrum protection, persistence, and increased yeast concentration levels against fungal infections (Cirvilleri, 2015). According to Wisniewski *et al*. (2016), these methods, when used together additively or synergistically, can achieve commercial-level (97–99%) disease control. The following Table 8 presents an overview of different biological control products and their effectiveness against various post-harvest pathogens.

Table 8: Biological Control Products and Their Effectiveness Against Post-Harvest Pathogens

Biological control product	Microbe base	Target crops	Target pathogen	reference
Candifruit	*Candida sake*	Pome fruit	*B cinerea, Penicillium* spp	Garrido *et al.* (2014)
Aspire	*Candida oleophila*	Citrus	*B cinerea, Penicillium spp*	Liu, Sui *et al.*, (2011)
Shemer	*Metschnikowia fructicola*	Grape, strawberry	*B. cinerea, Penicillium spp, Rhizopus spp, Aspergillus spp*	Droby *et al.*, (2009)

Strategic Outlook

The future of post-harvest disease management in fruit crops holds significant promise with emerging innovative strategies. One notable area of focus is the development of new biocontrol agents, such as Candi fruit, currently under study. Further research is imperative to enable their commercial release and widespread adoption. Additionally, there is a pressing need for fast, efficient, economical, and less space-consuming storage techniques that can significantly reduce post-harvest losses. Advancements in nanotechnology research are essential to address the limitations of conventional storage and packing methods, offering potential improvements in preserving the quality and safety of fruit crops during storage. Affordable packaging and storage solutions must be made accessible to farmers to mitigate on-farm and transportation losses, ensuring the economic sustainability of horticultural practices. Moreover, the implementation of farmer-supportive government policies is crucial to address storage and crop loss challenges, providing a robust framework for the adoption of these innovative strategies. These prospects underscore the need for continued research and development to enhance the effectiveness and accessibility of post-harvest disease management techniques, ultimately contributing to the stability and growth of the horticultural industry.

Conclusion

Postharvest diseases significantly impact the quality and shelf life of horticultural products, necessitating effective management strategies. The integration of various preharvest and postharvest treatments, including hot water treatments and biopolymer-based alternatives like Oligo-Chitosan, offers sustainable solutions for disease control. Chemical treatments, though effective, require careful application to mitigate environmental and health risks. Advances in eco-friendly treatments, particularly biopolymers, represent a promising direction for reducing reliance on synthetic fungicides. Future research should focus on optimizing these treatments and understanding their mechanisms to enhance their efficacy and applicability in commercial postharvest management systems.

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