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Postharvest Diseases of Vegetable Crops and Their Management

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Abstract

Vegetable crops have an important role in food and nutrition and maintain the health of soil. India is the second-largest producer of vegetables in the world with a 16% (191.77 MT) share of global vegetable production. Every year, diseases cause postharvest losses (40–60%) in vegetable crops due to their perishable nature under field (15–20%), packaging and storage (15–20%), and transport (30–40%). Profiling, detection, and diagnosis of postharvest vegetable pathogens (diseases) are essential for better understanding of pathogen and formulation of safe management of postharvest spoilage of vegetables. The vegetable produce is spoiled by postharvest pathogens and makes them unfit for human consumption and market due to the production of mycotoxins and other potential human health risks. Genera of fungal pathogens viz. *Alternaria*, *Aschochyta*, *Colletotrichum*, *Didymella*, *Phoma*, *Phytophthora*, *Pythium*, *Rhizoctonia*, *Sclerotinia*, *Sclerotium*, and bacterial pathogens viz. *Erwinia* spp., *Pseudomonas* spp., *Ralstonia solanacearum*, *Xanthomonas euvesicatoria* were recorded as postharvest pathogens on vegetable crops. Fruit rot incidence of several post-harvest pathogens viz. *Alternaria solani* (30%), *Phytophthora infestans* (15%), *Rhophitulus solani* (30%), *Sclerotium rolfsii* (30%) fruit rot and *X. euvesicatoria* (5%) canker on tomato; *Colletotrichum dematium* fruit rot (20%) on chili; *Phomopsis vexans* (60%) fruit rot on brinjal was recorded. *Didymella* black rot and *Colletotrichum* anthracnose were recorded on fruits of bottle gourd, pumpkin, ash gourd, and watermelon. Important leguminous vegetable crops are infected by postharvest pathogens viz. *Aschochyta pisi*, *Colletotrichum lindemuthianum* (Anthracnose), *Sclerotinia sclerotiorum* (white rot) and *Pseudomonas syringae* pv. *phaseolicola* (blight), *Sclerotinia* white rot, *Alternaria* blight. However, *Xanthomonas* black rot (10%) on cabbage and *Pectinovora* (*Erwinia*) soft rot (19%) were recorded as emerging post-harvest pathogens on cauliflower.

Keywords: vegetable diseases, plant pathogens, diseases management, seed-borne, soil-borne diseases

1. Introduction

India is the second-largest producer of vegetables in the world after China, and shares about 16% of global vegetable production [1]. Processed vegetables have been exported at a compounded annual growth rate in the volume of 16% and in value of 25% [2, 3]. Vegetables have a significant role in enhancing farm income,

sustainable global food as well as nutritional security. Vegetables suffer from several fungal and bacterial postharvest diseases [4–6]. Postharvest losses in vegetables are reported up to 30–40% owing to poor postharvest practices [7].

Fungicide is commonly applied for post-harvest disease control. Hot air, curing and hot-water brushing reduces disease incidence and increases the efficacy of antagonists. Biocontrol agents and botanicals may also reduce the amount of fungicide frequently used in postharvest disease management. Biocontrol of postharvest diseases of vegetable crops has great potential under storage conditions and biological products/biopesticides are available in the market. The biopesticides Ecogen US (Aspire™), Azotobactor (Bio-Save™), and Anchor (Yield Plus™) are involved to combine products with a low level of fungicide and salt solutions (calcium chloride or sodium bicarbonate @ 1–2%) and other food additives to improve efficacy against postharvest diseases. EcoSMART formulation based on rosemary oil, viz. EcoTrol™, Sporan™ (fungicide) and eugenol oil formulation Mataran™ (weedicides) are recognized as safe plant protectants. Therefore, the postharvest application of eco-friendly control methods may be exploited to manage the disease of vegetables.

2. Economical and health impact of postharvest diseases of vegetables

Postharvest diseases cause qualitative and quantitative losses of vegetables and make them unfit for human consumption due to potential health risks. A large number of postharvest diseases are caused by black, white, and yellow fungi-derived carcinogenic mycotoxins and mutagenic secondary metabolites [8]. Losses due to postharvest disease may occur during the handling of produce from harvest to consumption. Primary and secondary agricultural practices are also important and costs such as harvesting, packaging, and transport must be taken into account when estimating the value of the produce lost as a result of post-harvest wastage. Fresh vegetables are highly perishable, and they have relatively short shelf lives. Fresh vegetables are living, respiring tissues that start senescing immediately after harvest. They are mostly comprised of water, with most having 90–95% moisture content. Because of the perishable nature of vegetables, special skills are required for postharvest handling. *Aspergillus flavus* is a saprophytic soil inhabitant fungus that infects postharvest vegetables and produces carcinogenic secondary metabolite aflatoxin in tropical, subtropical, and temperate geographic regions of the world. It also causes animal and human diseases (causing aflatoxicosis and/or liver cancer) due to consumption of contaminated food and feed and through invasive growth (causing aspergillosis), which is often fatal to humans who are immunocompromised [9]. A holistic approach is needed for regulating aflatoxins under the trade/export market with biosecurity including bio-warfare, biodiversity, and biosafety for liberalized trade under the World Trade Organization (WTO) [10].

3. Challenges of postharvest losses in vegetable crops

Application of good postharvest management practices which are supported by good technologies and also improving postharvest systems will maintain the quality of vegetables and reduce quantitative losses. Losses in vegetables are the result of (i) poor knowledge about the right harvesting index; thus, a large proportion of the harvested beans are usually over-mature (ii) poor handling practices, such as the use of plastic sacks for bulk packaging and transportation

which results in mechanical damage that serves as entry points for disease-causing organisms leading to rotting of the pods (iii) poor transport practices such as the use of trucks that have no cover, thus exposing the produce to direct sunlight and high temperature (iv) the absence of low-temperature storage facilities and transport systems, and (v) rough handling practices during distribution in retail markets.

4. Causes of postharvest diseases

In general, postharvest diseases and losses of vegetables are incited by fungi and bacteria. Postharvest diseases are often classified on the basis of the infection as “quiescent” or “latent”, where the pathogen infects before harvest in the field. Examples of postharvest diseases arising from quiescent infections include anthracnose of various vegetables caused by *Colletotrichum* spp. and gray mold rot caused by *Botrytis cinerea*. Some pathogens infect vegetables after harvest during storage and transport, which is called postharvest infection e.g. nesting disease of pea caused by *Pythium* species or *Rhizopus* species. Microbes infect horticultural produce and spread rapidly due to a lack of natural defense mechanisms in the tissues of the produce. Management of postharvest spoilage is becoming a very difficult task because the pesticides/chemicals available are rapidly declining with consumer concern for food safety.

5. Detection of postharvest pathogens

Pathogens were isolated on agar medium and identified on the basis of macroscopic and microscopic analysis of colony and conidia/spore morphology by Microscopy, Sero-diagnostics (ELISA, Dot-blot assays), and nucleic acid (PCR) based methods.

Why do we need, want, or should detect emerging postharvest pathogens (diseases) in vegetable crops?

- Determine presence and quantity of the pathogen (s) for quarantine legislation.
- Assess the effectiveness of Integrated Disease Management (IDM) modules.
- Issuing of Sanitary and Phytosanitary (SPS) certificate vegetable produce for safe export/transboundary movement under trade.
- Quantify spatial and temporal pathogen populations in a specific location.
- Quantify pathogen populations in relation with regional and seasonal yield losses.

6. Postharvest fungal diseases

Common postharvest diseases resulting from wound infections initiated during and after harvest includes blue and green mold (*Penicillium* spp.) and transit rot (*Rhizopus stolonifer*). Important fungal genera of anamorphic postharvest pathogens include *Penicillium*, *Aspergillus*, *Geotrichum*, *Botrytis*, *Fusarium*, *Alternaria*,

Colletotrichum, *Phomopsis*, *Rhizoctonia*, *Sclerotium*, and *Sclerotinia*. The most important pathosystem of postharvest vegetables are gray mold (*Botrytis* spp.), white mold and watery soft rot (*Sclerotinia* spp.), cottony leak (*Pythium* spp.) and *Sclerotium* rot (*Sclerotium rolfsii*) [6].

6.1 *Sclerotinia*: rot

White mold (*Sclerotinia sclerotiorum*) appears in warm and moist weather (>95% relative humidity) and favors fungal growth on infected pods which develops as a white, fluffy mycelial mat often with large, irregular, black-colored sclerotia, typical of *S. sclerotiorum* [11–13]. Within the superficial mycelium, initially white but later hard dark black sclerotia are formed. Infected pods show brown discoloration and soft rot. The isolated fungus was identified as *S. sclerotiorum* based on morphological and cultural characteristics of the mycelia and sclerotia (Figure 1) [14].

6.2 *Ascochyta*: blight

Ascochyta blight (*Ascochyta pisi*) black spot symptoms on pods result in the production of round tan-colored sunken spots bearing dark margins. Pycnidia develop in the centers of such spots on pods (Table 1).

6.3 *Phytophthora*: late blight

Tomato (*Solanum lycopersicum*, solanaceae) is one of the most important vegetable crops. In the last couple of the years, the disease has become one of the most devastating threats to the cultivation of tomatoes in eastern Uttar Pradesh [15, 16]. Initial disease symptoms appeared in the form of irregular; water-soaked and light brown lesions on leaves which are normally covered with white cottony mycelial growth on the lower side of leaves. Water-soaked brown lesions expanded rapidly on stem and green fruits. Infected green fruits of tomato usually developed olivaceous, brown-colored leathery, and hard structures. All infected fruits eventually fall off from the plants and they were neither fit for marketing nor human consumption. Microscopic studies of the colonized pathogen on potato slices revealed hyaline, coenocytic, branched hyphae, and aseptate sporangiophores with lemon-shaped, papillate sporangia. Sporangia dimensions were $32 \pm 6.3 \times 20 \pm 4.9 \mu\text{m}$, with a length to width ratio of 1.6. On the basis of morphological characteristics and sporangia size, the pathogen was confirmed as *P. infestans* (Figure 2) [17].

6.4 *Colletotrichum*: fruit rot

Chili (*Capsicum annum*, solanaceae) is an economically important spice crop, widely grown in India. *Colletotrichum* sp. is an anamorphic fungal genera ranked in 8th position among top 10 fungal plant pathogens in the world. Infected fruits showing typical anthracnose symptoms of sunken necrotic lesions with a black dot like acervuli in concentric rings collected and collected fruit samples were examined under a light transmission microscope. Anthracnose (*Colletotrichum lindemuthianum*, *C. orbiculare*) symptoms appear on immature pods. Sunken cankers with lighter or gray central areas of about 5–7 mm size are seen. The spots on vegetable pods are enlarged and produce tiny black acervuli in the centers which in humid conditions ooze viscous droplets consisting of a mass of pinkish spores. Pure culture

Figure 1.
Typical symptoms of *Sclerotinia white rot* and culture plate. (A) Indian bean, (B) Indian bean, (C) French bean, (D) pea, (E) pea, (F) brinjal, (G) tomato, (H) bottle gourd, (I) PDA culture plate.

Pathogen	Disease	Symptom
<i>Sclerotinia sclerotiorum</i>	Watery soft rot or white stem rot	Disease symptom initially appears in the form of water-soaked lesions on pods and stems. Later, infected tissues become whitish and covered with white mycelia mats and black-colored sclerotia.
<i>Colletotrichum lindemuthianum</i>	Anthracnose	Disease symptoms appear in the form of brown to black sunken spots and lesions on leaves, stems, and pods. The center of anthracnose lesions on pods is covered with numerous black dot-like acervuli.
<i>Ascochyta pisi</i>	<i>Ascochyta</i> blight	Black spot symptoms on pods result in the production of round tan-colored sunken spots bearing dark margins with pycnidia on pods.
<i>Macrophomina phaseolina</i> (<i>Rhizoctonia solani</i>)	Charcoal rot or ashy stem blight	Disease symptoms appear in the form of dark brown to black charcoal-colored lesions covered with black dot-like fruiting bodies (resting microsclerotia and pycnidia) on pods.
<i>Sclerotium rolfsii</i>	Sclerotium rot	Whitish growth with mustard-like sclerotia on pods.
<i>Pythium</i> spp.	Cottony leak	White mycelial growth on pods.

Table 1.
Postharvest diseases/pathosystem of leguminous vegetable crops.

Figure 2. Typical Symptom of *Phytophthora blight* on tomato fruits and Sporangia. (A) Tomato, (B) sporangia.

Figure 3. Typical symptoms of *Colletotrichum* fruit rot (anthracnose), culture, and conidia. (A) Chili, (B) cowpea, (C) bottle gourd, (D) bottle gourd.

of the pathogen isolate was established on PDA by the hyphal tip method. Under the light microscope, one-celled, smooth-walled hyaline falcate, tapered ended conidia ($16\text{--}26 \times 3\text{--}4 \mu\text{m}$) and acervuli with numerous setae ($15\text{--}27 \times 2\text{--}5 \mu\text{m}$), were recorded. In this respect, this documentation will play an important role for better understanding of the pathogen and formulation of disease management strategies for the prevention of pre and postharvest crop losses under changing climatic scenarios (**Figure 3**).

6.5 *Didymella*: blight/rot

Gummy stem blight (GSB) is caused by *Stagonosporopsis cucurbitacearum* (syn. *Didymella bryoniae*). *S. cucurbitacearum* is an airborne, seed-borne and soil-borne facultative necrotrophic plant pathogen. A black dot like pycnidia is observed on the infected fruits. Its incidence was recorded on cucurbits such as cucumber, bottle gourd, ash gourd, watermelon, etc. in the field and poly-house. Inoculated PDA plates were produced white mycelium after 4 weeks of incubation at 24°C . Conidia were cylindrical non-septate to monoseptate and

Figure 4.
Didymella black rot, culture plate, and conidia. (A) Bottle gourd, (B) PDA culture plate, (C) conidia.

Disease	Pathogen	Incidence (%)
Black rot	<i>Didymella bryoniae</i>	50
Fruit spot	<i>Colletotrichum laginarium</i>	18–23
<i>Sclerotinia</i> rot	<i>Sclerotinia sclerotiorum</i>	10
Blossom blight	<i>Choanephora infundibulifera</i>	30

Table 2.
Postharvest diseases/pathosystems of cucurbitaceous vegetable crops.

Disease	Pathogen	Crop	Incidence (%)
<i>Phomopsis</i> fruit blight	<i>Phomopsis vexans</i>	Brinjal	40–60
<i>Sclerotinia</i> fruit blight	<i>Sclerotinia sclerotiorum</i>	Brinjal	5–10
Fruit blight	<i>Phytophthora infestans</i>	Tomato	15
<i>Sclerotinia</i> rot	<i>Sclerotinia sclerotiotrum</i>	Tomato	30
<i>Rhizoctonia</i> rot	<i>Rhizoctonia solanaii</i>	Tomato	30
<i>Alternaria</i> rot	<i>Alternaria solani</i>	Tomato	30
<i>Colletotrichum</i> fruit rot	<i>Colletotrichum dematium</i>	Chili	20

Table 3.
Postharvest diseases/pathosystems of solanaceous vegetable crops.

60 × 40 µm in size. Based on the morphological and microscopic characteristics, the pathogen was identified as *Stagonosporopsis cucurbitacearum* (syn. *Didymella bryoniae*) (Figure 4 and Table 2).

6.6 *Phomopsis*: blight

Brinjal (*Solanum melongena*, Solanaceae) is one of the most important vegetables worldwide. *Phomopsis vexans* is one of the notorious seed-borne fungal pathogens that causes destructive *Phomopsis* blight which ranked second topmost disease of brinjal in India (Table 3). Brinjal fruit rot due to the incidence of this disease has been estimated up to 60%. The pathogen was identified on the basis of colony morphology and size of conidia (20–40 × 40 µ) (Figures 5 and 6).

Figure 5. Typical symptom of Phomopsis, culture plate, and conidia. (A–B) brinjal, (C) brinjal, (D) PDA culture plate, (E) conidia.

Figure 6. Alternaria fruit rot (A–C) and Sclerotinia rot, culture and sclerotia. (A) Tomato, (B) tomato, (C) cauliflower, (D) tomato, (E) PDA culture plate, (F) sclerotia.

7. Postharvest bacterial diseases

Phytopathogenic bacteria cause postharvest diseases of economically important vegetables. Different species of bacteria belonging to top ten genera viz. *Pseudomonas*; *Ralstonia*; *Agrobacterium*; *Xanthomonas*; *Xanthomonas*; *Xanthomonas*; *Erwinia*; *Xylella*; *Dickeya* (*dadantii* and *solani*); *Pectobacterium* are devastating plant pathogens [18, 19]. They are unable to penetrate directly into plant tissue; however, they enter through wounds or natural plant openings. Wounds can be caused by insects and tools during operations like pruning and picking of the produce. The bacteria only become more active and cause infection when factors are conducive. Factors conducive to infection

are high humidity, crowding, poor air circulation, plant stress caused by overwatering, under watering, or irregular watering, poor soil health, and deficient or excess nutrients. The bacteria multiply quickly when free moisture and moderate temperatures are available. The major causal agents of bacterial soft rots are various species of *Erwinia*, *Pseudomonas*, *Bacillus*, *Lactobacillus*, and *Xanthomonas*. *Psuedomonas syringae* pv. *syringae*, *P. syringae* pv. *pisi* and *P. syringae* pv. *phaseolicola* causes diseases in vegetables [20]. The symptoms appear as water-soaked spots on pods that become sunken and dark-brown in color with distinctive reddish-brown margins.

Biological (culture media, diagnostic hosts, bacteriophages (phage typing); biochemical (based on properties of the bacteria in culture (gram stain, bacterial cell size, flagella), metabolic fingerprinting (API/BIOLOG system), thin layer chromatography, gel electrophoresis, conductance assays, isozyme analysis); immunoassays (agglutination, gel diffusion, ELISA, dot blot assays, immunofluorescence, flow cytometry); nucleic acid (hybridization, RFLPs, PCR, ICAN, DNA arrays, multilocus sequence typing) were used for reliable and accurate detection of plant pathogens for their effective management.

7.1 *Xanthomonas*: blight

X. campestris pv. *vesicatoria* now reclassified as *X. euvesicatoria*, the causal agent of bacterial spot of tomato. The disease is prevalent in warm, humid, and temperate regions of the world. The genus *Xanthomonas* comprises 20 different species [21] with many pathovars causing economically important diseases on different vegetable crops [22]. *Xanthomonas* is a rod-shaped, gram-negative bacterium. It produces a yellow soluble pigment, called xanthomonadin, and extracellular polysaccharide (EPS). EPS is an important pathogenicity factor of bacteria that protect from desiccation and for the attenuation of wind- and rain-borne dispersal (Figure 7).

7.2 *Pseudomonas*: blight

The disease is caused by pathogen, *Pseudomonas syringae* pv. *pisi*. Another bacterium, *P. syringae* pv. *syringae* has also been reported to infect vegetable pea in a temperate region. Tender pods are chocolate brown, thin, twisted, and

Figure 7. *Xanthomonas* blight (A and B) and *Pectobacterium* soft rot (C) and culture plate of *Xanthomonas* (D and E) and *Pectobacterium* sp. (A) *Xanthomonas* tomato speck, (B) *Xanthomonas* blight on kale, (C) *Pectobacterium* soft rot on cauliflower, (D) *Xanthomonas* NA culture plate, (E) *Xanthomonas* NA culture plate, (F) *Pectobacterium* NA culture plate.

Crop	Disease	Pathogen	Incidence (%)
Tomato	Soft rot	<i>Pectinovora (Erwinia) carotovora</i> pv. <i>carotovora</i>	5
	Bacterial speck	<i>Xanthomona</i> sp.	5
Chili	Soft rot	<i>Pectinovora (Erwinia) carotovora</i> pv. <i>carotovora</i>	2
Beans	Soft rot	<i>Pectinovora (Erwinia)</i> , <i>Pseudomonas</i> , <i>Bacillus</i> , <i>Lactobacillus</i> and <i>Xanthomona</i> sp.	5
Cabbage	Black rot	<i>X. campestris</i> pv. <i>campestris</i>	10
Cauliflower	Soft rot	<i>Pectinovora (Erwinia) carotovora</i> pv. <i>carotovora</i>	19
Summer squash	Soft rot	<i>Pectinovora (Erwinia) carotovora</i> pv. <i>carotovora</i>	5–10

Table 4.
Postharvest bacterial diseases/pathosystem of vegetable crops.

shriveled. Lesions are large on older pods and they become thin, twisted, and dry. Seeds become discolored and shriveled. Dried bacterial ooze makes the pod surface glossy.

7.3 *Pectobacterium*: soft rot

Pectobacterium carotovorum and *Pectobacterium atrosepticum* (formerly *Erwinia carotovora* subspecies *carotovora* and subspecies *atroseptica*) causes huge losses of economically important fleshy vegetables worldwide. *P. atrosepticum* was the first genomically sequenced plant bacterial pathogen that is taxonomically related to animal pathogens. Genomic information is now available for *P. carotovorum* strains and other “former *Erwinia*” species now reclassified in the genus *Dickeya*. Geographically, *P. carotovorum* is widely distributed and causes soft rot diseases of several vegetable crops. However, *P. atrosepticum* is an economically important pathogen of blackleg disease of potato and restricted into the temperate region of the world (Table 4) [23].

8. Postharvest disease management

Postharvest losses in vegetables are found due to fungal and bacterial infection worldwide. New challenges are faced under trade liberalization and globalization, and serious efforts are needed to reduce these losses in vegetables.

8.1 Chemical control

Chemical fungicides are commonly used for the management of postharvest disease in vegetables. For postharvest pathogens which infect produce before harvest, the fungicides should be applied at field level during the crop season, and/or strategically applied as systemic fungicides. At the postharvest level, the fungicides are often applied to reduce infections already established in the surface tissues of produce or they may protect against infections occurring during storage and handling. Fungicides used during postharvest are actually fungistatic rather than fungicidal under normal usage. The fungicides are applied on the produce as dips, sprays, fumigants, treated wraps, and box liners or in waxes and coatings. Dip and spray methods are very common in postharvest treatments. The fungicides

generally applied as a dip or spray method are benzimidazoles (e.g. benomyl and thiabendazole) against anthracnose, and triazoles (e.g. prochloraz and imazalil) and fumigants, such as sulfur dioxide, for the control of gray mold used for postharvest disease control [24, 25]. Dipping in hot water (at 50°C for 5–10 min, depending on the size of produce in combination with the fungicide) is also used for effective control of the disease. Sodium hypochlorite as a disinfectant is used to kill spores of pathogens present on the surface of the vegetable produce.

8.2 Biological control

International markets reject produce containing unauthorized pesticides, with pesticide residues exceeding permissible limits, and with inadequate labeling and packaging. Hence, biological control of postharvest diseases has great potential because postharvest environmental conditions like temperature and humidity can be strictly controlled to suit the needs of the biocontrol agent. Much information has been provided in relation to postharvest biocontrol and the problems faced by the development of commercial products [26, 27]. Biological control is used through microbes such as fungi, bacteria, actinomycetes, and viruses (bacteriophages) to control the postharvest disease of vegetables [1, 28–31]. The degree of disease control or disease suppression achieved with these bioagents can be comparable to that achieved with chemicals. As per estimates, the market of Indian bioagents is equivalent to 2.89% of the overall pesticide market in India with the worth of rupees 690 crores. It is expected to show an annual growth rate of about 2.3% in the coming years [32, 33]. In India, so far only 18 types of bio-pesticides have been registered under the Insecticide Act of 1968. Among agriculturally important microbes, *Trichoderma viride*, *T. harzianum*, *Pseudomonas fluorescens*, and *Bacillus subtilis* are the most potential bio-agents which act as producers of biologically active metabolites like antibiotics and bacteriocin, elicitors and inducers of systemic resistance in plants. Biocontrol mediated pathogen inhibition is found to be more effective when the antagonist is applied prior to infection taking place. Antagonists which act against postharvest pathogens of vegetables by competitive inhibition at wound sites include the yeasts *Pichia* and *Debaryomyces* species. Chitosan, for example, is not only an elicitor of host defense responses but also has direct fungicidal action against a range of postharvest pathogens. *Trichoderma* has potent antifungal activity against *Botrytis cinerea*, *S. sclerotiorum*, *Corticium rolfii*, and other important biotic stresses. Microbial pesticide active ingredients of *Streptomyces griseoviridis* K61 against bacterial soft rot, gray mold, *Phytophthora*; *Gliocladium catenulatum* against gray mold; *Candida oleophila* strain against postharvest diseases; *Coniothyrium minitans* against *Sclerotinia sclerotiorum*, *Sclerotinia minor*; *Trichoderma asperellum* (formerly *T. harzianum*) against *Pythium*, *Phytophthora*, *Botrytis*, *Rhizoctonia*; *Trichoderma atroviridae* against *B. cinerea* and *B. subtilis* against *Botrytis* spp. is the most commonly used biocontrol agents for postharvest diseases.

Antagonistic yeast forms a biofilm to stick pathogen and parasitize on the hyphae of the pathogen. Bar-Shimon et al. [34] reported that biocontrol efficacy of yeast correlates with the production of lytic enzymes and their ability to tolerate high concentrations of salts. Further, molecular approaches were used to examine the role of glucanases in the biocontrol activity of the yeast *C. oleophila* and biocontrol activity was enhanced by overexpression of antimicrobial peptides. By early 2000, three postharvest biological products, Aspire™ (the USA and Israel), Bio-Save™ (the USA), and Yield Plus™ (South Africa) were available in the market. However, Aspire was initially involved to combine the product with a low concentration of postharvest fungicide [35] or salt solutions (1–2%) of calcium

chloride or sodium bicarbonate and also with other additives which are commonly used in the food industry [36]. These products were also combined with physical treatments like hot air, curing, hot-water brushing, and combinations of the above with pressure infiltration of calcium for improvement of efficacy [37]. To increase bio-efficacy, the antagonists can also be combined with a sugar analogue (2-deoxy-D-glucose).

An effort has been made to develop two new products based on yeast antagonist *Candida saitoana* and a derivative of either chitosan (Biocoat) or lysozyme (Biocure). These products had been evaluated worldwide. They showed strong eradivative activity. The two commercial products based on the use of a heat-tolerant strain of *Metschnikowia fructicola* also contain other additives such as sodium bicarbonate. The additives are found highly effective to increase biocontrol efficacy to levels equivalent to those found with available postharvest fungicides. The product is marketed under the name ProYeast-ST and ProYeast-ORG in Israel by the company AgroGreen and found effective against rots incited by *Botrytis*, *Penicillium*, *Rhizopus*, and *Aspergillus*.

8.3 Plant essential oils

Botanical pesticides cause no adverse effects on non-target biota with biodegradability. It should be noted that most of the crops sprayed with botanical pesticides are quite safe for consumption after a short period after spraying. A large number of defensive of rich chemicals such as terpenoids, alkaloids, phenols, tannins, coumarins, flavonoids, etc. are present in plants which cause physiological effects on pathogens. These compounds have already been identified in the extracts/exudates of many plants. They have antimicrobial activities and are used for postharvest disease control.

The use of natural botanical products would be a supplement or an alternative to synthetic fungicide. Examples include 1,8-cineole, the major constituent of oils from rosemary (*Rosmarinus officinale*) and eucalyptus (*Eucalyptus globus*), eugenol from clove oil (*Syzygium aromaticum*), thymol from garden thyme (*Thymus vulgaris*), and menthol from various species of mint (*Mentha* species). The majority of research is progressing in this regard to develop plant oil-based pesticides. Therefore, essential oil-based formulations have great scope in the future to use as green pesticides as plant protectants in the integrated pest and disease management of value-added agriculture and horticulture crops.

Many exhaustive studies have been carried out on the utility of neem oil against various fungal pathogens. Its efficacy has been evaluated against fungal pathogens and found to be on par with the fungicide hymexazole in the control of the soil pathogens *Fusarium oxysporum*, *Fusarium ciceri*, *R. solani*, *S. rolfsii* and *S. sclerotiorum*. Researchers have reported *in-vitro* inhibition of 16 aromatic compounds against five major seed-borne fungal pathogens in the concentration range of 100–8000 ppm and the minimum inhibitory concentration (MIC) value for all the test fungi was 270–1704 ppm. Essential oils under commerce used as biopesticides have many problems, such as non-tariff barrier, scarcity of natural resources, need of quality control, and difficulties of registration. Some plant products have been commercialized. SPIC Science Foundation has developed a fungistatic product “Wanis” which has a single monoterpene as an ingredient and it is reportedly very effective in controlling more than 30 different types of phytopathogenic fungi. It is non-toxic to human beings and livestock. Recently, an antifungal agent by the name “TALENT”, containing carvone as the active ingredient, derived from the essential oil of *Carum carvi*, was commercialized. Mycotech Corporation product Cinnamite™, based on cinnamon oil, has been developed as a fungicide/miticide for

glasshouse and horticultural crops. World-leading essential oil-based pesticide producing EcoSMART technologies developed EcoPCORR under the name Bioganic™ as insecticide and miticide for nursery crops, horticultural crops, and value-added crops under glasshouse conditions. The EcoSMART formulation is based on rosemary oil, viz. EcoTrol™ (insecticide/miticide), Sporan™ (fungicide) and eugenol oil formulation Mataran™ (weedicides) were classified as generally recognized as safe (GRAS). The search for antifungal agents of plant origin is important, which can further broaden the arsenal for disease management and can be used as alternatives or complementary to synthetic fungicides. These chemicals of biological origin are safe to use, and in a few cases can even be produced by farmers and rural communities. Thus plant essential oils are safe to the user and the environment and have a good potential as crop protectants and integrated pest management under organic farming and value-added agricultural and horticultural crops [38].

9. Postharvest handling operations of vegetable crops

Maintenance of hygiene in all stages of postharvest handling is critical to minimize the source of primary inoculum for postharvest diseases [39]. Produce should be harvested during the day instead of early morning. Field containers should be smoothed. Containers should be cleaned. Sterilized packing and grading equipment, particularly brushes and rollers, are used. Chlorinated water @ 100 ppm is commonly used for washing vegetables. This can be done with chlorine gas or with either liquid hypochlorite (pH 6.0–7.0). Containers should not be overfilled, which causes severe damage during stacking. Management of temperature is the most important factor to extend the shelf life of fresh vegetables after harvest. It begins with rapid removal of the field heat by using any of the following cooling methods: hydro-cooling, in-package ice, top icing, evaporative cooling, room cooling, forced air cooling, serpentine forced air cooling, vacuum cooling, and hydro-vacuum cooling. The relative humidity during storage should be maintained at about 85–95% for most fruits and 95–98% for vegetables. Transport vehicles should always be cleaned and sanitized before loading.

10. Conclusion

For postharvest disease management, various strategies such as postharvest handling systems, sanitation, and integration of botanicals/plant essential oil, microbial bioagents, and safe chemicals need to be integrated and develop integrated postharvest diseases management techniques under World Trade Organization (WTO) regime. Among them, it is expected that the knowledge of biocontrol will lead to new, innovative approaches to minimize postharvest decay of the product and it presents the best hope for the future of postharvest disease management of vegetable produce. Future research in this field will include a better understanding of the molecular basis of variability in the pathogen, pathogenesis, accurate and reliable diagnostic of the disease and to engineer novel and durable protection strategies against devastating postharvest diseases of vegetable crops.

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