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Effect of natural compounds in management of post-harvest fungal diseases

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Abstract

Fungal pathogens cause extensive damage and reduce the quality of fruits and vegetables by 5% to 10% in developed countries and more than 50% in developing countries. Awareness of the dangers of synthetic fungicide residues on plant products and the increase in demand for organic products cause the current concerns about the purity of food and also desire to use environmentally safe compounds in control of fungal diseases after harvest of various crops. Therefore, a diverse range of essential oils and plant extracts and their effective compounds with strong antifungal, antiaflatoxicogenic effects and a wide range of antimicrobial effects are considered as suitable alternatives to synthetic fungicides in the management of post-harvest fungal pathogens on various fruits and vegetables.

Key words: Essential oils, Fruits and vegetables, Fungal diseases, Plant extracts

Introduction

Fungal species belonging to *Botrytis*, *Fusarium*, *Aspergillus*, *Penicillium*, *Alternaria*, *Colletotrichum*, *Lasiodiplodia*, *Phomopsis*, *Rhizopus*, *Phytophthora*, *Mucor*, Sclerotium and Sclerotinia genera are the most important post-harvest pathogens. Some fungal pathogens such as *Fusarium*, *Aspergillus* and *Penicillium*, in addition to causing rot are capable of producing mycotoxins, leading to fruit contamination and health risks for consumers [59]. Since the beginning of 1960, synthetic fungicides have been proposed as the most important commercial tools for controlling post-harvest diseases, and until now they are used in the practical control of most post-harvest fungal diseases of fruits and vegetables. However, there are many threats in the coming years, such as resistance in fungal pathogens and general fear of synthetic chemical fungicides, especially in fruits and vegetables [85]. Also, due to availability, safety and reasonable price, natural herbal products are proposed to manage such pathogens. The control of fungal diseases after the harvest of fruits and vegetables through each of the plant essences separately or in combination is an important factor in determining the successful factors of product marketing [79].

Antifungal herbal essential oils

Volatile aromatic compounds have been found in only 10% of plant branches and in secretory structures such as secretory glands, secretory ducts, secretory cavities, secretory hairs or resin ducts of plants [19] and also in the form of liquid droplets in various parts including leaves, stems, bark, flowers, fruits and roots are stored [44-53]. Plants contain 1-2% plant essential oil and sometimes 0.01-10% [13-49].

The inhibitory concentration values (IC50) of cinnamon essential oil (*Cinnamomum zeylanicum*) against *Alternaria solani*, *Botryodiplodia maydis*, *Fusarium graminearum*, *Pythium aphanidermatum* and *R. solani* are 0.09 mg/ml, 0.07 mg/ml, 0.08 mg/ml, 0.09 mg/ml and 0.08 mg/ml have been proposed, respectively [36]. Application of different concentrations of *Ferula asafoetida* essential oil is suggested as an effective control method against fungal pathogens, such as *Aspergillus niger*, *Fusarium oxysporum*, *F. moniliforme*, *F. nivale*, *F. semitectum*, *Drechslera hawinesis* and *A. alternate* [88].

The essential oil of Indian sweet basil (*Ocimum basilicum*) in the amount of 0.16% v/v led to the control of post-harvest anthracnose disease caused by *Colletotrichum musae*, collar rot caused by *Lasiodoiplodia theobromae*, *C. musae* and *Fusarium* sp. [71] and storage of bananas (Embul banana Musa acuminata-AAB) for 21 days in cold storage (13.51±1°C) without damaging the physical and chemical properties, for example, fruit and weight loss [5]. Cumin essential oil (*Cuminium cyminum* L.) with a concentration of 60 µl controls the fungal contamination of strawberries caused by *B. cinerea* and increases the shelf life of strawberries with a minimum period of time without affecting their quality [7] and essential oil *Chenopodium album* at 100 µg/ml concentration inhibits storage fungal pathogens after harvesting and significantly controls the production of aflatoxin B by *Aspergillus flavus* [52].

Basil (*Ocimum sanctum*), potar (*Cymbopogan citratus*), citronella grass (*C. nardus*) and grass (*C. martinii*) plant essential oils reduce the severity of diseases caused by post-harvest fungal pathogens such as *Rhizoctonia solani* and *Cylidrocarpon* sp. compared to the control at room temperature (28 ± 2°C) and cold storage (14°C) [80]. Also, spraying bananas (Embul M. acuminata AAB) with the emulsion of essential oil extract of cinnamon bark (*C. zeylanicum*) before storage leads to the control of fungal pathogens after harvest and increases shelf life for 14 days at ambient temperature (28 ± 2°C) and 21 days at a temperature of 14°C with 90% relative humidity [73].

Caesulia axillaris and *Mentha arvensis* essential oils with concentrations of 1500 and 1000 µl/l, respectively, lead to the control of *Pennicillium italicum* and increase the shelf life of oranges for 3 and 7 days, respectively, without the effect of plant toxicity [102]. Also, the essential oils of wild mint (*M. arvensis*), basil (*Ocimum canum*) and ginger (*Zingiber officinale*) inhibit the blue mold diseases of oranges and limes caused by *P. italicum* [97]. Basil essential oil (*O. sanctum*) increases the shelf life of oranges and limes for 6 days, and wild mint (*M. arvensis*) and ginger (*Z. officinale*) essential oils increase the shelf life of oranges and limes for 6 , 8 and also 4 and 8 days, respectively. Treatment with essential oils of basil (*O. sanctum*), peach (*Prunus persica*) and ginger (*Z. officinale*) increased the shelf life of grapes by more than 4, 5 and 6 days, respectively, and decreased gray mold development, caused by *B. cinerea* [96].

The essential oils of some plants, including eucalyptus (*Eucalyptus radiata* ssp. *radiata*), oregano (*Mentha pulegium*), rosemary (*Rosmarinus officinalis*), *Origanum compactum*, lavender (*Lavandula angustifolia*), cloves (*Syzygium aromaticum*), thyme (*Thymus vulgaris*) and orange (*Citrus aurantium*), are capable of controling brown rot of apple caused by *Monilinia fructigena* and *M. laxa*. Among these, the highest inhibition levels were observed by application of the essential oil obtained from *S. aromaticum* against *M. laxa* and *M. fructigena*, which were 64.7-94% and 63.9-94%, respectively [46].

The mechanism of action of plant essential oils

Citral, α-pinene and citronellal are known as major components of essential oils involved in preventing germination of fungal spores, and also cause changes in the morphology and decrease in the width of the fungal hyphae [31], rupture of the cytoplasmic membrane, cytoplasmic granulation of fungal cells and deactivation of extracellular and intracellular enzymes [20]. The antifungal activity of essential oils of basil (*O. basilicum*) and grass (*Cymbopogon martini*) led to control *Lasiodiplodia theobromae* and *Colletotrichum musae* and also reduce the activity of pectolytic enzymes such as Endo-PG and Exo-PG produced by the pathogens [80]. The lack of activity and normal structure of cells, organelles and macromolecules of *A. flavus* causes inhibition of growth parameters, sporulation and aflatoxin production [67] and also the effect of Citral on *A. flavus* spores causes damage to cell walls and membranes and induces production of malondialdehyde (MDA). They lead to a decrease in their volume and elasticity and interact with the amino groups of the membrane protein. After changes in the cell, biological oxidation and the tricarboxylic acid (TCA) cycle cause metabolic disorders by affecting the expression of mitochondrial genes and reproduction [56].

Antifungal compounds of herbal essential oils

Citral and α-pinene are the main hydrocarbons of plant essential oils, which are effective in control of fungal diseases. Citral vapor and its geranial and Citral isomers (2-6 µl/l) have inhibitory effects on post-harvest fungal pathogens such as *Penicillium digitatum*, *P. italicum*, *Geotrichum candidum* and the key fungi responsible for the spoilage of citrus fruits and apples after harvest, as well as inhibiting *P. expansum*, the cause of apple rot and blue mold [101-104]. Different combinations of plant essential oils, including citral, citronellal, L. carvone, isopullegol and α-pinene, can be used in management of fungal diseases with synergistic effect [29]. Application of some pure monoterpenes of essential oils, such as citral at a concentration of 0.5%, leads to growth inhibition of *C. musae*, *C. gloeosporioides* and *F. subglutinans* f. sp. *ananas* , as well as post-harvest treatment with citral at a concentration of 1%, which reduces papaya waste by 70% and banana waste by 60% [31].

Monoterpenes including camphor, artemisia ketone, 1,8-cineole, caryophyllene oxide, a-copaene and camphene are known as the main compounds of several essential oils. Gandwash essential oil (*Artemisia annua* L.) is effective in controling tomato late blight disease caused by *Phytophthora infestans* [93]. Essential oils obtained from Tarragon (*Artemesia dracunculus*), Kharagosh (*A. absinthium*), *A. santonicum* and *A. spicigera* contain compounds such as camphor, 1,8-cineole, chamazulene, nuciferol propionate, caryophyllene oxide, borneol, alpha-terpineol, cubenol, spathulenol, β-eudesmol and terpinen-4-ol and such compounds are capable of inhibiting *Phytophthora. capsici* growth and sporulation [48]. The flavonoid compounds Quercetin and luteolin of olive essential oil (*Olea europaea*) cause morphological changes and structural disturbance of *P. Megasperma* [10].

The main compounds of the aerial parts of *Artemisia Ludoviciana* essential oil, including camphor and cis-verbenol, are effective in control of *P. capsici* with inhibitory activity against fungus-like organisms belonging to oomycota [83]. Also, the main compounds of this essential oil such as camphor, borneol and cisverbenol inhibit plant pathogens including *Phytophthora cactorum*, *P. infestans*, *P. cinnamomi*, *P. capsici* and *P. mirabilis* [23]. The main anti-oomycota ingredients of thyme (*Thymbra spicata* ssp. *spicata*), marjoram (*Origanum syriacum* var. *bevanii*), rosemary (*Rosmarinus officinalis*), lavender (*Lavandula stoechas* ssp. *stoechas*), fennel (*Foenicure vulgare*) and bay leaves (*Laurus nobilis*) include carvacrol, anethole, camphor, borneol and 1,8-cineole, respectively, and have significant inhibitory effect against *P. infestans* [92].

Application of a solution containing combination of eugenol and lecithin with concentrations of 2 mg/ml and 50 mg/ml respectively at 50°C leads to control of the apple pathogen *P. expansum* by 60% and 90%, respectively [62]. Also, different formulations of eugenol essential oil, for example, the combination of 2 mg/ml of apple eugenol and 50 mg/ml of soy lecithin after 6 months of storage at 2°C reduces the spread of pathogenic agents after harvest, such as *P. expansum*, *B. cinerea*, *Monilinea fructigena* and *Phlyctema vagabunda* [4]. Several compounds, such as eugenol, β-selanine and β-caryophyllene have been identified as the main components of basil essential oil (*O. basilicum*) by gas chromatography, as well as citral α and citral β, myrcene and limonene as the main components of lemon grass essential oil (*C. citratus*) which were detected by gas chromatography and mass spectrometry. Application of carvacrol obtained from the essential oil of thyme (*T. vulgaris*) and marjoram (*O. majorana*) and ρ-anisaldehyde lead to the antifungal effect of the above essential oils [15].

Evaporation of eucalyptus (*Eucalyptus globulus* L.) and cinnamon (*Cinnamomum zeylanicum*) essential oil compounds at 13°C storage temperature reduces the rotting of strawberries and tomatoes caused by *Phytophthora fragariae* and *Fusarium oxysporum*, respectively [98]. Biofumigation of apricots with thymol vapor at a concentration of 2 mg/l leads to 2% decrease in conidial germination of apricot (*Prunus armeniaca*) compared to 98% of the control, and also fumigation of apricots with thymol at a concentration of 5 mg/l causes a decrease of 3%. Disease incidence compared to 64% of control fruits [55] and cherry disinfection with thymol at a concentration of 10 mg/l cause a significant reduction of sweet cherry brown rot caused by *Monolinia fructicola* [18].

Chemical compounds of plant essential oils destroy cell membrane proteins and deposit cell protein, leading to the leakage of amino acids of pathogenic agents and inactivation of enzymes involved in pathogenesis such as cellulase and pectinolytic enzymes, as well as natural plant compounds such as *chrysanthemum pyrethrum* (*Chrysanthemum cinerariefolium*) and Neem azadirachtin (*Azadiracta indica*) protects agricultural products against fungal pathogens [34]. Acetaldehyde controls pathogenic *B. cinerea* and *Rhizopus stolonifer* in strawberries and hexanal reduces the survival of *P. expansum* spores on open apples for 48 hours under laboratory and in vivo conditions [8]. Also, the compounds of acetaldehyde, benzaldehyde as the most toxic, 6-carbon-aldehyde, hexal and hexanal in a concentration of 0.4% µl/ml control *A. alternata*, *B. cinerea* and *C. gloeosporioides* [99]. Terpenes including carvacrol, p-cymene and thymol as antifungal compounds of essential oils of basil (*O. vulgare*) [35-70] and chemical compounds B-pinene, γ-terpinene and cuminaldehyde as the main components of cumin essential oils (*Cuminum cyminum*) [14] are reported and with a concentration of 200 µg/ml are involved in controling 88% of *Pseudoallescheria boydii* and 19% of *F. oxysporum* f. sp. *lycopersici* [72].

Table 1. Antifungal active compounds of plant essential oils

Plant essential oil	Common name	Active component	Reference
Ocimum basilicum	Basil	Thymol	[67]
Ocimum gratissimum	Wild basil	Thymol	[1]
Ocimum sativum	Basil	Thymol	[90]
Cymbopogon citratus	Lemongrass	Citral Geranial neral	[67-100]
Cymbopogon martini *Cinnamomum zeylanicum*	Palmarosa Cinnamon	Geraniol Cinnamaldehyde eugenol	[100]
Thymus vulgaris	Thyme	Carvacrol Linalool Thymol	[90]
Trachyspermum ammi	Ajowan	Thymol	[69]
Azadiracta indica	Neem	Oleic acid Hexadecanoic acid	[91]
Brassica spp.	Mustard	Allyl isothiocyanate	[25-26]
Cuminum cyminum L.	Cumin	y-Terpinene cucumin aldehyde	[7]
Trachyspermum ammi	Ajowan	Thymol	[69]
Thymus Matichina	Thymus	Linalool	[30]
Melaleuca aternifolin *Pinus* spp. *Mentha spicata*	Tea tree oil Pine Spearmint	Terpinen-4-ol y-Terpineol l-Carvone	[47]
Syzygium aromaticum	Clove	Eugenol	[74]

Antifungal plant extracts

Various chemical compounds [33] in response to fungal pathogens and the stresses caused by them [66-75] as well as many plants secondary metabolites with low molecular weight such as essential oils, phenols, alkaloids, flavonoids, quinones, tannins and saponins are secreted [27]. In general, the antimicrobial compounds of medicinal plants are divided into the chemical groups of phenolic compounds, phenolic acids and polyphenols, flavonoids and isoflavonoids, tannins, coumarins, terpenoids, lectins and polypeptides [82], as well as some secondary metabolites with activity antifungals are classified into phytoanticipin and phytoalexin compounds with low molecular weight such as diterpenes, sesquiterpenes, isoflavonoids and coumarins [65].

Due to the lack of stability of the active compounds of plant extracts, it is necessary to purify the extracts in order to obtain effective compounds for control of plant diseases [82]. Active and inactive compounds of crude extracts or plant solvent parts are directly separated through thin-layer chromatography (TLC), as well as the antifungal activity of plant compounds through NMR (Nuclear magnetic resonance) spectroscopy, gas chromatography-spectroscopy. The mass is identified by GC-MS (Gas chromatography-mass spectrometry) or by comparing with standards. In general, the inhibitory effect of plant compounds on fungal cells, including cytoplasmic granulation of fungal cells, rupture of the cytoplasmic membrane, and inhibition of the synthesis of intracellular enzymes often lead to the destruction and death of the mycelium or propagule of fungal pathogens [94].

Aqueous extracts of papaya leaves (*Carica papaya*) and *Dyospiros ebenaster* extracts are mentioned as one of the management methods for pawpaw rot (*Asimina triloba*) and mango anthracnose caused by *Colletotrichum gloeosporioides*, respectively [11]. Pineapple treatment with *Xanthium stramarium* extracts and banana treatment with Thai eggplant leaf extracts (*Solanum toruvum*) led to complete control of *Ceratocystis paradoxa,* causing fungal rot [22] and banana anthracnose caused by *Colletotrichum musae* compared to benomyl fungicide 0.1% and increase the shelf life of fruits for 16 to 20 days compared to untreated fruits [95]. Garlic (*Allium sativum*) extracts containing the main antimicrobial compound allicin with diverse cellular target sites [21] reduce the intensity of potato infection caused by *Phytophthora infestans* and the outer colored layer of grapefruit peel (*Citrus paradise*) containing 7-geranoxy Coumarin inhibits *Penicillium italicum* and *P. digitatum* [89].

Treatment with alcoholic extracts of *Cerbera odollam* with concentration of 300 ppm inhibited 90% of citrus rotting pathogens such as *P. digitatum*, *Aspergillus niger* and *Fusarium* sp. [87] and treatment with spinach (*Spinacia oleracea*) and rhubarb (*Rheum ribes* L.) leaf extracts led to induction of systemic resistance in cucumber against *Colletotrichum lagenarium*. Treating bananas with zimmu leaf extract obtained from a cross between onion (*Allium cepa*) and garlic (*A. sativum*) increased the shelf life of bananas, controls rotting pathogens such as *Lasiodoiplodia theobromae* and *Colletotrichum musae* and induced systemic resistance through increasing the level of peroxidase (PO), polyphenol oxidase (PPO) and phenylalanine ammonialase (PAL) [81]. Ethanol extracts of medicinal plants including carrot seeds (*Daucus carota*) and pomegranate peel (*Punica granatum*) can control fungal pathogens, such as *Trichophyton violaceum* and *Microsporum audouinii* by 60.7-63.4% and 64.5-68.6%, respectively [6].

The extracts of *Sanguisorba minor* and *Orobanche crenata* control germination of conidia and reduce the length of germ tube of pathogens after harvesting, including *Monilinia laxa*, *Botrytis cinerea*, *Penicillium digitatum*, *P. italicum* and *Aspergillus niger*. Also, *S. minor* extracts containing caffeic acid derivatives and flavonoids prevent brown rot of apricots and nectarines, and *O. crenata* extracts reduce gray mold, brown rot, and green mold on grapes, apricots, nectarines, and oranges, respectively [6]. The extracts of wild safflower (*Carthamus lanatus*) and nutmeg (*Myristica fragrans*) have a significant inhibitory effect against the diseases caused by *Phytophthora drechsleri* [3] and *Phytophthora infestans*, respectively [17]. *Eupatorium cannabinuin* leaf extracts with 1:1 dilution control *Pythium debarynum* and the combination of ajoin obtained from garlic (*A. sativum*) prevents the germination of *Phytophthora* sp. extracts of cardamom (*Elettaria cardamomum*), ginger (*Zingiber officinale*) and galangal with different concentrations of 10%, 20% and 30% have significant antifungal effect of 100% against *Phoma exigua*, *Fusarium* nygamai and *Rhizoctonia solani* [51].

Aqueous leaf and flower extracts of *Datura metel* L. prevent the activity of some fungi including *Trichoderma harzianum*, *T. viride*, *Fusarium oxysporum* f. sp. *melonis*, *F. oxysporum* f. sp. *lycopersici* and *F. oxysporum* f. sp. *tuberosi*. Investigations revealed the highest inhibition rate (69%) of aqueous extracts of *D. metel* flowers on *T. viride* and high sensitivity of *F. oxysporum* f. sp. *melonis* compared to the above organic extracts as well as the abundant fungicidal activity of leaf extracts on *F. oxysporum* f. sp. t*uberosi* compared to *D. metel* flower extracts [76].

Table 2. The inhibitory effect of plant products and extracts on fungus-like organisms

Plant species	Target pathogen	Disease	Experimental condition	Reference
Ageratum houstonianum *Tephrosia vogelli* *Clausena anisata*	*P. infestans*	Potato late blight	-	[32]
Allium sativum *Medicago sativa*	*P. capsici*	Blight of pepper	Pot field	[24]
Azadirachta indica *Curcuma longa* *Zingiber officinale* *Ocimum sanctum* *Datura stramonium* *Allium cepa*	*P. aphanidermatum*	Fruit rot of muskmelon	Greenhouse field	[86]
Salvia officinalis *Malva silvestris* *Ocimum basilicum*	*P. infestans*	Potato late blight	Greenhouse	[50]
Salvia officinalis *Potentilla erecta* *Salix* sp. *Rheum rhabarbarum* *Malva silvestris* *Sophora flavescens* *Ocimum basilicum*	*P. infestans*	Tomato late blight	Laboratory Growth chamber Field	[28]
Salvia officinalis	*Pseudoperonospora cubensis*	Cucumber downy mildew	Pot field	[63]
Hedera helix *Paeonia suffruticosa*	*P. infestans*	Tomato late blight downy mildew of cucumber	Detached leaf Greenhouse	[78]

Bioactive metabolites are mainly classified into the main groups of alkaloids, terpenoids and phenolics. Phenolic compounds as the most abundant metabolites of plants with one or more aromatic rings and one or more hydroxyl groups attract pollinators, symbionts and protect plants against pests and pathogens. Many phenolic compounds of plants such as phenolic acids as the most important polyphenols of plants with diverse functions such as interactions between plants and microbes, flavonoids, tannins, stilbenes and lignins have inhibitory activity against oomycota fungi and also the most common phenolic acids such as gallic acid and caffeic acid have antifungal activity and inhibition against oomycota [60-64].

Caffeic acid as an inhibitor of plant cell protein kinase C and its ester as rosmarinic acid extracts of rosemary (*Salvia rosmarinus*) and lavender (*Lavandula angustifolia*) [9-61] with concentrations of 3 g/l and 6 g/l, respectively causes complete control of zoospores mobility of *Phytophthora capsici*, *P. megakarya* and *P. palmivora* [103]. Caffeic acid of sage (*Salvia officinalis*) and rice (*Oryza sativa*) extracts reduces the germination of cysts of oomycota, and caffeic acid of olive (*Olea europaea*) leads to the control of *Pythium* spp. [2]. The active compounds of *Anemarrhena asphodeloides* extracts include nyasol and 1,4-pentadiene (Z)-1,3-bis(4-hydroxyphenyl) with antifungal activity. They reduce the disease caused by *P. capsici* and *Pythium ultimum* [37-68]. Quercetin and luteolin flavonoid compounds of olive (*Olea europaea*) cause morphological changes and structural disturbance of *P. megasperma* [10] and isoflavonoids claussequinone, medicarpin and formononetin reduce the activity and mobility of zoospores of phytopathogens [42].

Zoosporicidal activity of extracts of Indian ash (*Lannea coromandelica*) and commercial polyflavonoid tannins including Mimosa and Quebracho against *A. cochlioides* is the same [41], and also the aforementioned polyflavonoid tannins cause destruction of zoospores of downy mildew in cucumbers and grapes caused by *Plasmodium viticola* [39-43]. Active phenolic compounds N-trans-feruloyltyramine and linoleoyl-2-lysophosphatidic acid monomethyl-1 ester of purslane (*Portulaca oleracea*) extracts stimulate and inhibit the motility of *A. cochlioides* zoospores, respectively [58]. Phosphatidic acid induces the blocking of zoospores of *P. palmivora* as well as G-protein, di-octanoyl phosphatidic acid, butanol and mastoparan lead to the stimulation of zoospores blockage of *Phytophthora infestans* [54]. The neolignans of magnolia bark extracts (*Magnolia obovata*) including methoxyhonokiol-4, honokiol and obovatol have significant biocontrol effect against *P. capsici* and *P. ultimum* [16]. Antifungal lignans nectandrin-B, erythro-austrobailignan-6 and methanolic in the extracts of *Myristica fragrans* seeds reduced tomato late blight development caused by *P. infestans* [17].

Amaranthus gangeticus plant extracts contain N-trans-feruloyl-4-O-methyldopamine and nicotinamide compounds and prevent the absorption and mobility of *A. cochlioides* zoospores [40-84]. A higher level of nicotinamide than N-trans-feruloyl-4-O-methyldopamine from the roots of this plant, as well as higher levels of N-trans-feruloyl-4-O-methyldopamine and lower levels of nicotinamide from different types of *A. gangeticus* are secreted [38]. The phenolic active compounds N-trans-feruloyltyramine and linoleoyl-2-lysophosphatidic acid monomethyl-1ester of purslane extract (*Portulaca oleracea*) are respectively stimulating and inhibiting the motility of zoospores of *A. cochlioides* [58].

Table 3. Effect of plant bioactive metabolites on different life stages of pseudofungal pathogens

Compounds	Source plant	Pathogen	Bioactivity	Reference
Caffeic acid Rosmarinic acid Coumaric acid Ferulic acid	*Olea europaea*	*Pythium* sp.	Mycelial growth inhibition	[2]
Camphor Artemisia ketone 1,8- Cineole Caryophyllene oxide a-Copaene Camphene	*Artemisia annua* L.	*P. infestans*	Conidial germination Germ tube elongation inhibition	[93]
Oleuropein Protocatechuic acid Cinnamic acid	*Rosmarinus officinalis* *Lavandula angustifolai*	*P. palmivora* *P. megakarya* *P. capsici*	Inhibition of cystospore germination	[103]
Polyflavonoid tannins	*Lannea coromandelica*	*A. cochlioides*	Zoospores motility inhibition	[41]
Nyasol	*Anemarrhena asphodeloides*	*P. capsici* *P. ultimum*	Mycelial growth inhibition	[68]
(±)-Medicarpin (–)-Claussequinone Formononetin	*Dalbergia odorifera*	*A. cochlioides*	Zoospore repellants	[42]
Magnolol Honokiol 4-Methoxyhonokiol Obovatol	*Magnolia obovata*	*P. capsici* *P. ultimum*	Mycelial growth inhibition	[16]
Isoeichlerialactone Isoeichlerianic acid aglinin A	*Aglaia forbesii*	*P. botryose* *P. palmivora*	Mycelial growth inhibition	[45]
Anacardic acids Cardol Cadanol	*Ginkgo biloba*	*A. cochlioides*	Motility inhibition Lysis of zoospores	[12]
Nicotinamide	*Amaranthus gangeticus*	*A. cochlioides*	Zoospore attraction Motility inhibition	[40]
Nicotinamide	*Amaranthus gangeticus* *Pisum sativum*	*A. cochlioides* *A. euteiches*	Zoospore motility inhibition	[84]
Coumestrol biochanin A Naringenin Sorhamnetin Quercetin Isoquercitrin	*Glycine max*	*P. sojae*	Mycelial growth inhibition Hyphal tip swelling Increase oogonia number Lag phase prolongation	[77]

Table 3 (Continue). The effect of plant bioactive metabolites on different life stages of pseudofungal pathogens

Compounds	Source plant	Pathogen	Bioactivity	Reference
Quercetin Luteolin Rutin Oleuropein p-Coumaric acid Tyrosol Catechin	*Olea europaea* L.	*P. megasperma*	Mycelial growth inhibition Ultrastructure disruption	[10]
Camphor 1,8-Cineole Chamazulene Nuciferol propionate Nuciferol butanoate Caryophyllene oxide Borneol a-Terpineol Spathulenol Cubenol b-Eudesmol Terpinen-4-ol	*Artemisia dracunculus* *A. absinthium* *A. santonicum* *A. spicigera*	*P. capsici*	Mycelial growth inhibition	[48]
Carvacrol Borneol Camphor Anethole 1,8-Cineole	*Origanum syriacum* var. *bevanii* *Thymbra spicata* ssp. *spicata* *Lavandula stoechas* ssp. *stoechas* *Rosmarinus officinalis* *Foeniculum vulgare* *Laurus nobilis*	*P. infestans*	Mycelial growth inhibition Cytoplasmic coagulation Vacuolations Hyphal shriveling Protoplast leakage	[92]
Nootkatin Carvacrolc Valencene Nootkatone	*Chamaecyparis nootkatensis*	*P. ramorum*	Hyphal growth inhibition Zoospore lysis	[57]
Neoverataline A and B Veramitaline Stenophylline B Triadimefon	*Veratrum taliense*	*P. capsici*	Mycelial growth inhibition	[105]

Conclusion

Postharvest fungal diseases cause damage to fruits and vegetables during transportation and storage. The combination of rich nutrients, humidity and pH cause the activation of some pathogenic microorganisms and rotting of fruits and vegetables. Evaluation of biological activity and application of natural compounds is essential to control post-harvest diseases of fruits and vegetables. It is very important to find compounds of natural origin and resistance inducing properties to manage post-harvest fungal diseases. Therefore, ecologically appropriate approaches for management of plant diseases are needed as a way to develop sustainable disease control. Increasing research in the field of protection of agricultural products with the use of essential oils and natural plant extracts leads to the development of successful and effective strategies and increasing the quantity and quality of organic plant products.

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