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Natural products for postharvest decay control in horticultural produce: a review

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Abstract

Purpose of review: This review offers a perusal of reports on the use of natural products for postharvest decay control in fresh horticultural produce. In light of research findings, it considers the use of natural products for postharvest decay control in horticultural produce.

Main findings: Important wastage of produce occurs in the postharvest chain, of which decay, caused by various postharvest pathogens, dictates a considerable part. The use of synthetic fungicides has faced limitations and restrictions owing to their teratogenicity, acute residual toxicity, long degradation period, and other effects on human health and the environment. Biodegradable and eco-friendly natural compounds such as flavour compounds, acetic acid, jasmonates, glucosinolates, chitosan, essential oils and active principles of some plants have gained importance and attention for their use as decay-control agents and safer alternatives to synthetic chemicals. Encouraging results on the use of natural products to control postharvest decay indicate the possibility of developing natural fungicides that would be as effective as synthetic fungicides, and yet are safe for man and environment.

Directions for future research: Coordinated and continuous search for natural products may yield safer alternatives for postharvest decay control. Research efforts need to be directed towards establishing the mode of action of the products so as to provide important guidance for their application. Natural products that are found efficacious during *in vitro* and *in vivo* studies should be considered for commercial application. Emphasis should be placed on developing these products which can be used easily by the end users.

Keywords: postharvest decay; flavour compounds; jasmonates; acetic acid; glucosinolates; chitosan; essential oils; plant extracts

Abbreviations

MeJA	Methyl Jasmonate
GRAS	Generally Regarded as Safe
AITC	Allyl isothiocyanate

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Introduction

The horticultural sector constitutes a major portion of the production and trade of agricultural produce. Of several horticultural produce, fruits and vegetables are considered as protective foods as they play a beneficial role in human health. Fresh fruits and vegetables have low pH, high moisture and nutrient composition which make them highly susceptible to pathogenic attack. As a result considerable postharvest losses of fruits and vegetables are brought about by decay causing pathogens [1**]. With the availability of limited land resources for agricultural expansion and the looming food security threat posed by global climate change, reduction in postharvest losses would be the most feasible option to meet the present and future food needs of the ever-increasing hungry and under-nourished population.

Pesticides have been the primary means of controlling postharvest diseases in horticultural produce. It is generally accepted that production and marketing of these perishable products would not be possible without their use [2]. Nevertheless, the disadvantages outweigh the benefits due to excessive and indiscriminate use of synthetic chemicals. Thus, restrictions on their use have evolved owing to their carcinogenicity and teratogenicity [3], high and acute residual toxicity, long degradation period, environmental pollution [4], effects on food [5] and humans [6], high cost and development of resistance to commonly used chemicals [7, 8]. Hence, efforts have been made to develop alternative strategies that are safe to humans and to the environment [9], as well as to reduce losses due to postharvest decay. Significant success has been achieved through the use of non-chemical methods, non-selective fungicides and physical treatments such as heat therapy, low temperature storage, irradiation etc [10–12]. Microbial antagonists (biocontrol agents) have also been investigated as an alternative to synthetic chemicals for control of postharvest diseases [13]. However, the effectiveness of a single microbial culture against a single postharvest pathogen, decreasing efficacy during storage and lack of consistency have plagued their commercialisation.

Several natural compounds rank highly among the alternative strategies that are currently being investigated for controlling postharvest decay of horticultural produce. This review attempts to deepen our understanding and knowledge on the use of several of these natural products for controlling postharvest decay in horticultural produce.

Natural compounds

Among the common natural compounds used for postharvest decay control in horticultural produce are flavour compounds, acetic acid, jasmonates, chitosan, essential oils, plant extracts, among others. Investigations into each of these natural products will be discusses in subsequent sections.

Flavour compounds

Flavour compounds are secondary metabolites having unique properties of volatility, and fat and low-water solubility. The advantages in the use of such flavour compounds include easy adsorbtion, less chance of off-odours, a harmless nature in mammalian systems, and a high efficacy even when applied in low concentrations.

Acetaldehyde

Acetaldehyde is a flavour compound produced by ripening fruits. Such compounds have been used for postharvest decay control. The fruit volatiles produced by ripening peaches have been found to be highly fungicidal [14]. Shaw *et al.* [15] suggested that the rot resistance of strawberries in high CO_2 storage was due to the production of high levels of acetaldehyde and ethyl acetate by the fruit. Prasad and Stadelbacher [16] have also reported the control of postharvest decay of fresh raspberries with the application of acetaldehyde vapour. The inhibitory action of acetaldehyde on postharvest microorganisms such as *Erwinia carotovora*, *Pseudomonas flourescens*, *Monilinia fructicola* [17], *Penicillium* sp. [18] and yeast [19] has been reported on several fruits and vegetables.

Hexenal

Hexenal is another flavour compound that has strong antifungal activity [20, 21**]. Use of hexenal is reported to control various postharvest pathogens. For example, fumigation of 'Crimson Seedless' table grapes with (E)-2-Hexenal resulted in efficient control of mould [22] and inhibited hyphal growth of *Penicillium expansum* and *Botrytis cinerea in vitro* and on apple slices [23]. Six carbon (C_6) aldehydes have also been found to inhibit hyphal growth of *Alternaria alternata* and *B. cinerea* suggesting that hexenal and similar aldehydes have the potential to be used against postharvest decay pathogens of fresh horticultural produce [21]. Almenar *et al.* [24] studied the efficacy of inclusion complex β-cyclodextrin-hexanal against postharvest pathogens like *Colletotrichum acutatum*, *A. alternata* and *B. cinerea*, and found that the sustained release of hexanal from the complex could reduce or prevent postharvest diseases in berries. Furthermore, the best control of blue mould of apple and pear caused by *P. expansum* was achieved by treating the fruits with 12.5 μL/L of trans-2-hexenal [25*]. Similarly, continuous controlled release of hexanal effectively suppressed grey mould of tomato caused by *B. cinerea* [26].

Acetic acid

Acetic acid is a metabolic intermediate that occurs naturally in many fruits [27]. It is considered as an effective fumigant for surface-sterilising a wide range of horticultural produce. Acetic acid vapour in pure form [28] or as vinegar [29] is a very effective treatment for reducing postharvest decay in several horticultural commodities. Its effectiveness in preventing postharvest fruit decay caused by postharvest pathogens like *Penicillium digitatum*, *B. cinerea*, *P. expansum*, *M. fructicola* and *Rhizopus stolonifer* is well documented. For eg, Sholberg and Gaunce [30**] reported acetic acid as a very effective postharvest fumigant for controlling the decay caused by *M. fructicola* and *R. stolonifer* on peaches, *Alternaria* rot of sweet cherries and brown rot caused by *M. fructicola* on apricots. Banwart [31] attributed the inhibitory effect of acetic acid to its undissociated nature that can penetrate the microbial cell to exert its toxic effect. Even low concentrations of acetic acid have been shown to effectively control *B. cinerea* on apples [32]. Fumigation with acetic acid prevented postharvest decay in table grapes [33, 34]. These results suggest the use of acetic acid vapour as a potential replacement for SO_2 fumigation, which is currently employed on a commercial scale for decay control in stored grapes. In addition, commercial use of acetic acid as a fumigant has been reported in apricot and plums [35], and sweet cherries [36–38]. The best postharvest control of decay caused by *P. digitatum* in 'Fremont' and 'Fairchild' mandarins was achieved by combining curing and acetic acid vapour fumigation [39]. Furthermore, acetic acid vapour proved to be very effective in disinfecting d'Anjou pear stems and fruit surfaces [40**]. However, if acetic acid vapour is to be used for large volumes of fruit, extreme care must be taken in monitoring its concentration and maintaining it at a safe level.

Jasmonates

Jasmonates are naturally occurring plant growth regulators, belonging to a class of olypines, which have been implicated in the regulation of various processes of plant development and responses to environmental stresses [41–43]. They play an important role as signal molecules in plant defence responses against pathogen attack and activate genes encoding antifungal proteins such as thionin [44], osmotin [45] and genes involved in phytoalexin biosynthesis [46, 47]. Methyl jasmonate (MeJA), a major derivative of the plant hormone jasmonic acid, plays a critical role in inducing resistance to fungal pathogens. MeJA has been used effectively as a postharvest application in several fruits. For eg, MeJA has been reported to suppress *B. cinerea* in strawberry [48] and *P. digitatum* in 'Marsh Seedless' grapefruit [49]. Treatment of loquat fruit with MeJA resulted in significantly lower incidence of postharvest anthracnose rot caused by *C. acutatum* [50**]. Furthermore, MeJA along with antagonistic yeast *Pichia membranefaciens* significantly inhibited the growth of *C. acutatum* which causes postharvest anthracnose rot in loquat fruit [51]. Biocontrol efficacy of *Rhodotorula glutinis* was enhanced by the addition of MeJA for control of postharvest blue mould rot of pears caused by *P. expansum* [52]. Yao and Tian [53] reported that pre and postharvest application of MeJA resulted in lower incidence of brown rot of sweet cherries caused by *M. fructicola* during storage. Furthermore, exposure of papaya (*Carica papaya* L., cv. Sunrise) fruit to MeJA vapours (10^{-5} or 10^{-4} M) for 16 h at 20°C inhibited fungal decay caused by *Colletotrichum gloeosporioides* [54]. Pulsing of cut rose flowers with MeJA provided systemic protection against *Botrytis* rot by inducing resistance mechanisms in the treated cut roses without impairing flower quality [55]. Similarly, treatment of cut freesia variety Cote d'Azur flowers with MeJA vapour suppressed petal specking caused by *B. cinerea* infection [56]. Spore germination and production of *Colletotrichum coccodes* was suppressed when tomato fruits were treated with MeJA vapours, which ultimately led to reduction in the incidence of anthracnose rot [57]. Similarly, *Botrytis* rot symptoms were reduced in tomato fruit when treated with MeJA [58*]. The treatment of strawberries with 1 µmol/L MeJA significantly inhibited the fruit decay caused by *B. cinerea* during storage, probably by the induction of defence enzyme activities [59].

Glucosinolates

Glocusinolates are natural substances that are produced by crucifers. These substances have potential antimicrobial activity, and thus, inhibits the growth and spead of postharvest pathogens [60]. Commendable work on the postharvest antipathogenic activity of glucosinolates, particularly of allylisothiocyanate (AITC), has been carried out by Ishiki *et al.* [61], Delaquis and Maaza [62] and Mari *et al.* [63, 64]. For example, vapour phase antifungal activity of AITC against blue mould rot in apple caused by *P. expansum* has been observed [65, 66]. Isothiocyanates used at 0.03 mg/mL completely inhibited the growth of *A. alternata in vitro*, while a concentration of 0.56 mg/mL, in combination with low density polyethylene bags, performed better than the commercial fungicide in controlling fungi rot on bell pepper with no adverse effect on fruit quality [67]. Similarly, AITC was effective in retarding blueberry decay during storage at 10°C [68*].

Propolis

Propolis is a natural resinous substance obtained from leaf buds and bark of poplar and conifers [1**]. Extracts of propolis have antibiotic, antibacterial and antifungal activity [69], while Lima *et al.* [70] observed that propolis application significantly inhibited postharvest pathogens like *B. cinerea* and *P. expansum* and thereby, controlled postharvest decay effectively.

Fusapyrone and deoxyfusapyrone

Fusapyrone is a metabolite obtained from cultures of *Fusarium semitectum*. Its use for decay control has been promoted owing to its low toxicity towards animals and absence of phytotoxic effects [71]. Fusapyrone applied at 100µg/mL inhibited the growth of *B. cinerea* on grapes [72].

Chitosan

Chitosan, a deacylated form of chitin, is a natural biodegradable compound derived from the crutaceous shells such as crabs and shrimps. Chitosan has been very widely studied for its plant protective and antifungal properties and is known to trigger defensive mechanism in plants against pathogenic attacks. Several studies reveal that it holds potential for commercial postharvest decay control. For eg, it induced resistance in harvested Red Delicious apples rather than by direct inhibition of the pathogen [73]. El Ghaouth *et al.* reported that chitosan prevented the maceration of host tissues (bell pepper) by *B. cinerea*. Chitosan was not only effective in reducing the production of polygalacturonases by *B. cinerea*, but also caused severe cytological damage to the invading fungal hyphae [74**]. Available literature reveals that postharvest diseases of horticultural produce can be reduced/ controlled effectively by the use of chitosan as summarised in Table 1.

Essential oils

Essential oils derived from various plants have antipathogenic activity [90–94] and control phytopathogenic microorganisms [95]. The antifungal activity of essential oils of *Monarda citriodora* var. *citriodora* and *Melalenca alternifolia* on postharvest pathogens has been evaluated by Bishop and Thornton [96], while Tzortzakis and Economakis [97*] reported the antifungal activity of lemon-grass essential oil against key postharvest pathogens like *Colletotrichum coc-*

Table 1: Postharvest pathogens/diseases of horticultural produce and their control by chitosan.

Crop	Postharvest disease/pathogen	Reference (s)
Apple (*Malus x domestica*)	*P. expansum*	[78]
Grapes (*Vitis vinifera*)	*B. cinerea*	[81]
Grapes (*V. vinifera*)	*Colletotrichum* sp.	[79]
Litchi (*Litchi chinensis*)	Browning and decay	[86]
Longan (*Euphoria longana*)	Decay	[87]
Papaya (*Carica papaya*)	*C. gloeosporioides*	[85]
Peach (*Prunus persica*)	*M. fructicola*	[89]
Potato (*Solanum tuberosum*)	*Fusarium sulphureum*	[76]
Tangor (*Citrus tangerina*)	*Penicillium* sp.	[80]
Tomato (*Solanum lycopersicum*)	*B. cinerea*	[75]
Tomato (*S. lycopersicum*)	*Colletotrichum* sp.	[79]
Tomato (*S. lycopersicum*)	*B. cinerea and P. expansum*	[88]
Strawberry (*Fragaria x ananassa*)	*B. cinerea*	[82–84]
Sweet cherry (*Prunus avium*)	*Monilinia laxa*	[77]

codes, B. cinerea, Cladosporium herbarum, R. stolonifer and *Aspergillus niger*. Similarly, the essential oil of *Pimenta dioica* has been reported to inhibit pathogens like *Fusarium verticillioides*, *P. expansum*, *Penicillium brevicompactum*, *Aspergillus flavus* and *Aspergillus fumigatus* [98]. Furthermore, essential oils also controlled black mould rot of onion caused by *A. niger* [99]. Postharvest fungal diseases on flower bulbs could be controlled with essential oils [100], as well as blue mould rot on mandarins [101]. The essential oil from *Thymus vulgaris* exhibited antifungal activity against *B. cinerea* and *R. Stolonifer*, the storage pathogens of strawberry [102]. Storage of tulip bulbs in atmospheres containing cuminaldehyde, perillaldehyde, salicylaldehyde or carvone resulted in a significant reduction in *Penicillium hirsutum* infection [103]. Sharma and Tripathi [104] observed inhibition of mycelial growth, loss of cytoplasm and cell wall disruptions of fungus *A. niger* on treatment with essential oil from *Citrus sinensis* (L) Osbeck epicarp. Cassia oil at 500 µL/L significantly inhibited *A. alternata* of cherry tomatoes stored at 20°C for 3 days [105]. Arrebola *et al.* [106] reported that *Bacillus amyloliquefaciens* in combination with thyme and lemon-grass essential oils improved the beneficial effect of modified atmosphere packaging in retaining the overall fruit quality of peaches during storage. The essential oils of *Caesulia axillaris* and *Mentha arvensis* controlled the blue mould rot of oranges caused by *P. italicum* and enhanced the market life for a considerable period [107]. *Mentha spicata* and *Lippia scaberrima* essential oils, as well as pure (*d*)-limonene and R-(−)-carvone, amended coatings applied postharvest to 'Tomango' oranges resulted in excellent control of decay caused by *P. digitatum* [108]. Similarly, Cassia and thyme essential oils exhibited strong inhibitory and antifungal activity against postharvest pathogen (*A. alternata*) of cherry tomato [109].

Essential oil of *Lippia scaberrima* caused inhibition of mycelia growth of postharvest pathogens of mango such as *Botryosphaeria parva* and *C. gloeosporioides* and use of wax coating, enriched with essential oil, reduced the fungal infection during storage [110]. Essential oil from *Hyptis suaveolens* effectively reduced the pathogen population of *Fusarium oxysporum* f. sp. *gladioli* during storage of gladiolus corms [111, 112]. The postharvest decay in peaches, kiwifruit, oranges and lemons caused by fungi, namely *B. cinerea, Monilinia laxa* and *P. digitatum,* was effectively controlled by laurel oil as evidenced by postharvest decay inhibition in peaches, kiwifruit, oranges and lemons. A mixture of eugenol (2 mg/mL) and soy lecithin (50 mg/mL) reduced the disease incidence caused by *P. expansum*, *Penicillium vagabunda, B. cinerea* and *Monilinia fructigena* in apples to less than 7, 6, 4 and 2%, respectively after 6 months of storage at 2°C [113]. Cinnamon oil-enrichment resulted in significant reduction of colony development and spore formation in postharvest pathogens like *C. coccodes, B. cinerea, C. herbarum, R. stolonifer* and *A. niger* [114]. Romero *et al.* [115] observed that carvacrol vapour treatment resulted in significant reduction in postharvest decay and spoilage of stored table grapes. Valero *et al*. [116] studied the effect of combination of MAP with eugenol and thymol on table grapes and observed lower microbial spoilage up to 56 days of storage.

Thymol

Thymol is a natural monoterpene phenol derivative found in the oil of thyme. The United States Food and Drug Administration lists thymol, thymol essential oil and thyme as food for human consumption, as well as food additives. Thymol has been quite effective in controlling postharvest pathogens in horticultural commodities. For eg, postharvest brown rot of apricot and plums could be effectively controlled when fruits were fumigated with thymol even at low concentrations of 2 or 4 mg/L [117]. Furthermore, Chu *et al.* [37, 38*] reported effective control of postharvest gray mould rot in sweet cherries with thymol fumigation. Similarly, Zhao *et al.* [118] observed the antimicrobial activity of thymol derivative, 8-hydroxy-9, 10-diisobutyloxythymol, from the roots of Inula hupehensis against *Staphylococcus aureus*, *Escherichia coli*, *Rhizoctonia solani*, *Phytophthora melonis* and *Peronophythora litchi*, thereby, suggesting the possibility of postharvest antimicrobial decay control with this natural compound. Postharvest treatment with thymol vapours controls brown rot of stonefruits caused by *M. fructicola* [119]. Valero *et al.* [120] reported significant reduction in microbial spoilage in grapes under active packaging, developed by adding thymol and eugenol.

Carvone

Carvone is a natural terpenoid found in many essential oils. It is abundantly found in the oils from caraway (Carum carvi) seeds. Carvone has been reported to exhibit fungicidal activity against decay of potato tubers, besides suppressing sprouting in storage [121].

Menthol

Menthol is an organic compound obtained from peppermint or other mint oils. It is effective in controlling several diseases of fruits during storage. For eg, blue mould rot of oranges was effectively controlled with essential oils of *M. arvensis*, *Ocimum canum* and *Zingiber officinale* [122], suggesting a synergistic effect between the components. When fruits and vegetables are treated with menthol, the pathogen cannot easily develop resistance and, as a result, confers protection from decay during postharvest storage.

Plant extracts

Bioactive compounds extracted from plants or agro-industrial residues have great potential as novel fungicide sources for controlling pathogenic fungi. Several plant extracts have shown inhibitory action against postharvest pathogens. Although the preservative nature of some plant extracts has been known for centuries, the antimicrobial properties of extracts of aromatic plants have received renewed attention for only a decade or so. To date several studies have been conducted on the use of plant extracts in postharvest disease control in horticultural produce. The aqueous extract of leaves of garlic creeper (*Adenocalymna alliaceum* Miers) is reported to have antifungal activity [123]. Similarly, the polyphenolic extracts from *Larrea tridentata* leaves, pecanut (*Carya illinoensis*) shells and pomegranate (*Punica granatum*) husk displayed high efficiency in inhibiting the mycelial growth of *Pythium* sp., *Colletotrichum truncatum, C. coccodes, A. alternata, F. verticillioides, F. solani, F. sambucinum*, and *R. solani*, thereby, suggesting their potential use as antifungal agents [124*]. The antimycotic activity of *Piper betle* against fruit pathogens has also been reported by Mohamed *et al.* [125], and that of fresh juice and aqueous extracts of turmeric and ginger by Kapoor [126]. The extract of seeds of grapefruit alone or in combination with chitosan, significantly reduced postharvest gray mould rot of 'Redglobe' table grapes and maintained their keeping quality [127]. Bergeson *et al.* [128] isolated four active principles, viz. Irilin A, Irilin B, flavonone dihydrowogonin and sesquiterpene pygmol from aerial parts of *Chenopodium procerum* and observed the inhibition of growth on plant pathogenic fungus *Cladosporium cucumerinum*. Agnioni *et al.* [129] reported the inhibitory activity of 7-geranoxy coumarin, a compound isolated from tissue of 'Star Ruby' grapefruit against postharvest pathogens like *P. italicum* and *P. digitatum*. Strong antifungal activity of kaempferol, a compound extracted from *Acacia nilotica*, against *P. italicum* has been reported by Tripathi *et al.* [130]. Nowadays, a citrus seed extract (LonlifeTM, Citrex) is used as a postharvest treatment at a concentration of 250 ppm. This organic fungicide gives satisfactory control of crown and peel rot in several commodities in organic niche markets [131].

Conclusion

Over the years a wide range of chemicals has been used for the control of postharvest losses in horticultural produce and despite the efficacy, their indiscriminate use has only added to the problems. The ill-effects of chemicals on human health and environment have prompted the search for safer alternatives for postharvest decay control. Natural products have been actively examined for their anti-microbial activity. Encouraging results in this regard have indicated the potential for development of natural fungicides that could be as effective as synthetic chemicals for postharvest decay control. These products have the added advantage that they are perceived by the consumer as being more acceptable as these are generally regarded as safe (GRAS). However, before any recommendation can be given, these products should be thoroughly evaluated for their effect on organoleptic and other quality parameters, besides establishing their lowest possible dose of application and the mode of action. However, a number of issues still need to be resolved before commercialisation of these products can occur [132]. Furthermore, most of the products need to be applied at much greater concentrations than the levels at which they occur naturally in produce. Nonetheless, it is perceived that natural products would ultimately replace synthetic chemicals for the control of postharvest decay in horticultural produce.

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