Postharvest Biology and Technology 122 (2016) 70–81

Contents lists available at ScienceDirect

Postharvest Biology and Technology

journal homepage: www.elsevier.com/locate/postharvbio

Decay control in the postharvest system: Role of microbial and plant volatile organic compounds

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ARTICLE INFO

Article history:
Received 23 December 2015
Received in revised form 18 April 2016
Accepted 21 April 2016
Available online 6 May 2016

Keywords:
Essential oil
Isothiocyanate
Biofumigation
Biobased product
Postharvest losses
Volatile organic compounds

ABSTRACT

Significant postharvest losses occur during the supply chain of fresh produce. Postharvest decay is one of the main factors that determines losses and compromises the quality of fruit and vegetables. Traditionally postharvest decay control is achieved using chemical fungicides; however, the important concerns relating to environmental and human health require the development of novel methods for the control of postharvest decay. Furthermore, the consumer demand and the purchasing power are higher for fresh produce that are free from pesticide application. This review highlights the research literature based information on the application of microbial and plant volatile organic compounds (VOCs) to control postharvest decay, their practical applications in postharvest systems and the future perspectives. The volatile nature of VOCs could be potentially employed with success as gaseous treatments in a process defined 'biofumigation'. Plant-produced volatiles including among others, aldehydes such as acetaldehyde, 2-*E*-hexenal and benzaldehyde, alcohols such as ethanol and acetic acid, essential oils (EOs) and isothiocyanates (ITCs) and microbial volatile organic compounds have been recognised as potential substances in preventing pathogenic infections in many horticultural commodities. However, some issues have to be well elucidated in order to admit these substances in a large-scale application to improve the competitiveness of the fresh produce at the quality stringent EU, USA, and the Japanese markets. The main concern are related to the registration process, but also VOCs degradation and residues in fruit, formulation and organoleptic impact, are aspects that have to be thoroughly considered prior to commercialisation of the selected VOC. Furthermore, VOCs could have an effective role for an eco-chemical approach in postharvest disease control since these biobased products, if compared to conventional ones, can offer clear environmental benefits due to their renewability, biodegradability and hypotoxicity.

1. Introduction

Postharvest decay of fruit and vegetable presents a major factor causing postharvest losses and limits the duration of storage and shelf-life of produce. In addition, postharvest diseases contribute significantly to a deterioration of quality and nutrient composition, mycotoxin contamination and reduction of the market value of fruit. Traditionally, postharvest decay control is obtained using chemical fungicides, however their intense use has aroused important issues relating to environmental and human health, prompting to search for safer control means. Furthermore, consumers prefer purchasing fruit with few pesticide residues or better, none at all, thus inducing importing countries to reinforce strict import regulations regarding the maximum residue limits in the edible portion of the fruit (Sivakumar and Bautista-Baños, 2014). Therefore, alternatives are desirable for a sustainable management of the storage losses and among them, natural compounds, well known since antiquity for their antimicrobial and preservative properties (Burt, 2004) can play an important role in the fruit postharvest system. The responsible authorities to set the standard limits of pesticides will vary according to the country. Additionally the maximum residue limits of pesticides will depend on a particular vegetable or fruit (http://ec.europa.eu/sanco_pesticides/public/index.cfm). Generally, any biological molecule could be considered to be a natural product, but normally, the term is reserved for secondary metabolites (carotenoids, phytosterines,

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http://dx.doi.org/10.1016/j.postharvbio.2016.04.014
0925-5214/

saponines, phenolic compounds, alkaloids, glucosinolates, etc.) produced by an organism-like plant, bacterium, yeast, or fungus. Some of these secondary products exhibit a volatile nature and could be potentially employed with success as gaseous treatments in a process defined 'biofumigation'. The term, introduced originally to describe soil-borne pest and disease control by glucosinolate-containing plants (Kirkegaard et al., 1998), has been adopted to describe, for example, the control of fungal decay in blueberry fruit with plant essential oils (Mehra et al., 2013), the prevention of citrus postharvest molds with the endophytic fungus *Nodulisporium* spp. (Suwannarach et al., 2013), and the control of grey mold in strawberries with glucosinolate-derived allyl-isothiocyanate (Ugolini et al., 2014).

Volatile organic compounds (VOCs) typically constitute a complex mixture of low-molecular weight lipophilic compounds derived from different biosynthetic pathways, and to describe their complexity, the term 'volatilome' has been recently proposed (Maffei et al., 2011). VOCs are important components of the plant's chemical phenotype; leaves, flowers and fruits release them into the atmosphere, and roots, into the soil. Their primary functions are the defense against herbivores and pathogens, the attraction of pollinators and seed dispersers, and the signaling involved in plant–plant communication (Pichersky et al., 2006); in some plants, the VOC release may also act as a wound sealer (Dudareva and Pichersky, 2008). Microbial volatile organic compounds (MVOCs) are a type of VOC produced by all microorganisms as part of their metabolism. They are essential to exchange fundamental information about the molecular basis of microbial activities (Thorn and Greenman, 2012) and some species-specific MVOCs may also serve as marker compounds for the selective detection of fungal and bacterial species in the environment (Fiedler et al., 2001).

The antimicrobial activity of VOCs and MVOCs has been widely reviewed during recent years (Mari et al., 2011; Sivakumar and Bautista-Baños, 2014). Such antimicrobial activity was evident in different host-pathogen interactions, making them extremely attractive, in particular, because of their scarce toxicity at low concentrations. Integration of one or more different strategies to achieve higher levels of disease control and the inclusion of VOCs derived from plants and microorganisms will contribute to a successful handling of postharvest diseases.

This review deals with the substantial progress obtained in the use of VOCs and MVOCs as an alternative control measure of fruit postharvest diseases, also taking into account constraints and obstacles that hamper their large diffusion and practical application.

2. VOCs derived by plants

A significant number of VOCs derived from fruit and vegetables with antimicrobial activity against postharvest fungi have not yet been fully explored. Lately, there has been an increase in the recognition of plant-produced volatiles, including aldehydes such as acetaldehyde, 2-*E*-hexenal and benzaldehyde, alcohols such as ethanol and acetic acid, essential oils (EOs) and isothiocyanates (ITCs) that have been reported to be very effective in preventing pathogenic infections in many horticultural commodities. The importance of these aromatic and flavour compounds also lies in their low toxicity effects on humans, which renders many of them GRAS (Generally Regarded as Safe) compounds and applicable in safe treatments for USA market, although in the pesticide database, provided by European Commission (http://ec.europa.eu/food/plant/pesticides/eu-pesticides-database-redirect/index_en.htm), not all compounds classified as GRAS are approved as fungicides like ITCs, acetaldehyde, 2-*E*-hexenal, and benzaldehyde, while some essential oils such as thyme, clove, and mint oil are included in the approved pesticide list.

2.1. Aldehydes

2.1.1. Acetaldehyde

Acetaldehyde (AA) is a well-studied organic compound produced by different fruits and accumulates during ripening (Pesis, 2005). This compound is biosynthesized from pyruvic acid by the enzyme pyruvate decarboxylase. AA vapours have been evaluated *in vitro* against *Botrytis cinerea*, *Rhizopus stolonifer* and *Monilinia fructicola* (Prasad and Stadelbacher, 1974; Aharoni and Stadelbacher, 1973). In these studies, conidial ability to germinate was seriously affected by its application after some hours of exposure to this compound. In further studies, it was confirmed that AA applications completely deterred mycelial development of *Alternaria alternata* (Abd Alla et al., 2008). According to Utama et al. (2002), minimum inhibitory concentration (MIC) values ranged from 0.88 to 0.91 mmol $dish^{-1}$ reduced the growth of *R. stolonifer*, *Penicillium digitatum*, *Colletotrichum musae*, and *Erwinia carotovora*. As for Almenar et al. (2007) this antifungal volatile was also very effective in totally reducing the growth of *C. acutatum* over a 7-day period at 23 °C at concentrations of 0.56 $\mu L L^{-1}$. However, on this matter, Wood et al. (2013) reported that AA, applied at any concentration, did not inhibit the growth of serious postharvest pathogens of potato such as the fungi *Colletotrichum coccodes*, *Helminthosporium solani* and the bacterium *Pectobacterium atrosepticum*. Other microorganisms prone to be controlled by these vapours at concentrations at a minimum of 0.5% are various species of yeasts such as *Cryptococcus difluens* and *Schizosaccharomyces pombe* pathogens present in processed grape juices (Barkai-Golan and Aharoni, 1976).

For fumigation purposes, in fresh 'Midway' strawberry and 'Sultanina' and 'Perlette' grape, AA has shown to significantly reduce gray mold and Rhizopus rots during storage (Prasad and Stadelbacher, 1973). For strawberries, the concentration of 10% completely inhibited both rots; while for grapes, reduction of soft rot was approximately 90% at 0.25% concentration after 8 days storage. Similarly, infections caused by *P. expansum* in Tangelo 'Minneola' fruit (*C. reticulata* Blanco × *Citrus* × *paradisi*) were effectively controlled by AA fumigation. In this study, conidial survival on the fruit surface was 100% controlled after 12 h exposure (Arras et al., 1996). For bacterial postharvest diseases, the application of AA has also produced satisfactory results, according to Utama et al. (2010) since the symptoms caused by *E. carotovora* in 'Bell Tower' bell peppers (*Capsicum annum* L.) were delayed and notably reduced when AA was applied in plastic polyethylene containers. The study notes that the control of the pathogen during storage was dependent on the applied concentration and exposure times.

2.1.2. Benzaldehyde

Benzaldehyde is an organic compound consisting of a benzene ring with a formyl substituent. It is the simplest aromatic aldehyde and one of the most industrially useful. This colourless liquid has a characteristic pleasant almond-like odour. Benzaldehyde is the primary component of bitter almond oil and can be extracted from a number of other natural sources. This plant volatile is commonly found in fruits occurring as a volatile oil. It is a flavour compound identified to have antifungal effects. Evaluation of its effectiveness on various major postharvest fungi has been proven. In this regard, Wilson et al. (1987) reported that spores of *B. cinerea* and *M. fructicola* were unable to germinate at one concentration (1250 $\mu L L^{-1}$); however, mycelial growth reached a total inhibition at a lower concentration of 370 $\mu L L^{-1}$. Other *in vitro* studies also reported the fungicidal effect of this organic compound against some postharvest pathogens, including *E. carotovora* (Utama et al., 2002). However, Sun et al. (2014) reported no antimicrobial activity on *P. digitatum* when benzaldehyde was used in vapour and