

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository: <https://orca.cardiff.ac.uk/id/eprint/62746/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

Scariot, Valentina, Paradiso, Roberta, Rogers, Hilary Joan and De Pascale, Stefania 2014. Ethylene control in cut flowers: classical and innovative approaches. *Postharvest Biology and Technology* 97 , pp. 83-92. 10.1016/j.postharvbio.2014.06.010

Publishers page: <http://dx.doi.org/10.1016/j.postharvbio.2014.06.01...>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



2
3 **Ethylene control in cut flowers: classical and innovative approaches**

4
5 Valentina Scariot¹, Roberta Paradiso², Hilary Rogers³, Stefania De Pascale²

6 ¹ Department of Agricultural, Forest and Food Sciences University of Turin (Italy)

7 ² Department of Agricultural Sciences, University of Naples (Italy)

8 ³ School of Biosciences Cardiff University (UK)

9
10 Corresponding author

11 Roberta Paradiso, roberta.paradiso@unina.it

12 Department of Agricultural Sciences, University of Naples Federico II, Via Università,
13 100

14 80055 - Portici - Naples (Italy). Phone N. +39 081 2539135

15
16 **Key words**

17 Post harvest, nanosensors, nanocomposites, nanocatalyst, nanoparticles,
18 nanosponges,

19
20 **Highlights**

- 21 - Potential applications of nanotechnology in ethylene control for cut flowers
22 - Nanoparticle-based sensors for detecting ethylene throughout the distribution chain
23 - Nanocomposites as scavengers for ethylene removal in active packaging
24 - Nanocatalysts to promote ethylene catalytic degradation in the warehouse
25 - Nanoparticles and nanosponges as carriers of drugs for ethylene action inhibition

26
27 **Abstract**

28 Ethylene-mediated premature floral senescence and petal or flower abscission affect
29 postharvest longevity of several species used as cut flowers. Exposure to exogenous
30 or endogenously produced ethylene can be controlled in several ways. These include
31 the use of ethylene biosynthesis inhibitors or ethylene action inhibitors, and ethylene
32 removal technologies. In addition, genetic modification can be very effective in
33 controlling ethylene synthesis and perception. We review here the potential for

applications of nanotechnology to control ethylene levels and postharvest management in the flower industry. Already nanosponges have been shown to enhance efficacy of the ethylene inhibitor, 1-MCP, in several flower species. In carnation, 1-MCP included in nanosponges also allowed better control of *Botrytis cinerea* damage. However other applications are also considered based on successes in the use of this technology to increase agricultural production and decrease postharvest waste. Nano-metal based sensors could be used for detection of ethylene in the store and to label the product along the distribution chain. Furthermore, nanocomposites could be included as scavengers for ethylene removal in active packaging, and nanocatalysts could promote ethylene catalytic degradation in the warehouse. Nanoparticles could also be introduced into a new generation of packaging to control effects of gases and UV, and increase strength, quality and packaging appearance. This review highlights recent results on the use of nanotechnology *sensu lato* and potential application for cut flower vase life improvement, focusing on ethylene control strategies.

Contents

1. Introduction

1.1 Role of ethylene in floral senescence

1.1.1 Ethylene as an endogenous and exogenous regulator

1.1.2 Plant species: sensitivity and effects

1.2 Ethylene control strategies

1.2.1 Genetic strategies

1.2.2 Environmental strategies

1.2.3 Chemical strategies

2. Nanotechnology for ethylene control

2.1 Nanotechnology for ethylene detection and removal in the postharvest environment

2.1.1 Sensors using nanoparticles for the detection of ethylene

2.1.2 Nanocomposites and nanocatalyst for ethylene removal and photodegradation

2.2 Nanoparticles and nanoporous materials for ethylene action inhibition

3. Conclusions

1. Introduction

Postharvest performance is a key factor in the commercial value of cut flowers. Although external quality criteria such as appearance, colour and uniformity, are the major variables that influence the consumer's decision to purchase cut flowers, their longevity is fundamental to convince the consumer to re-purchase them (Reid and Jiang, 2012). As a fresh commodity and because of their extreme sensitivity, cut flowers are vulnerable to large postharvest losses. In addition to developmental senescence, cut flowers are also subject to leaf discoloration, premature wilting, and disease from moulds and fungal pathogens. An integrated approach is therefore adopted to maintain quality throughout the distribution chain to reduce water loss (e.g. avoiding high temperatures), control disease (such as *Botrytis* and *Alternaria*) and to limit cut flower ageing (avoiding prolonged cold storage).

Advances in postharvest science and technology aim to provide information for the horticultural industry to enable them to supply attractive and long-lived flowers to consumers. Indeed in the last ten years substantial progress in postharvest technologies has been achieved including novel packaging, storage and transport systems, pest and disease control for market access, senescence control, supply chain optimization, and track and trace systems to ensure delivery of premium quality products to markets (Toivonen, 2007; Michailides and Manganaris, 2009; Sharma, 2010). Chemicals are used extensively in modern agriculture in order to improve yield and quality. However, their use poses environmental and public health concerns. Many chemicals that affect ethylene synthesis or its action, which are currently in use to extend the shelf life of flowers, may be soon banned due to their environmental impact. Over the last decades, environmentally and health-friendly production methods and conscientious use of resources have become crucial for reaching the goal of more sustainable plant production. techniques and systems need to be developed. Thus further progress will require an integration of available bio-, info- and nano-technologies through a systems biology approach.

1.1 Role of ethylene in floral senescence

Ethylene is a simple molecule composed of two carbon atoms symmetrically linked to by a double bond and it naturally occurs in gaseous form. It is, furthermore, a plant growth regulator involved in the regulation of a wide range of different physiological processes, including germination, growth, floral initiation and opening, both leaf and floral senescence as well as organ abscission and fruit ripening (Yoo et al., 2009).

1.1.1 Ethylene as an endogenous and exogenous regulator

Floral lifespan is often terminated by the abscission of petals that are still turgid, or by petal wilting or withering. In many species, these processes are regulated by the plant growth regulator, ethylene (van Doorn, 2001; van Doorn and Woltering, 2008) through changes in endogenous levels. Plant tissues synthesize small amounts of ethylene ($0.1\text{--}0.2\ \mu\text{l Kg}^{-1}\text{ h}^{-1}$; Martínez-Romero et al., 2007). However ethylene production changes during plant development and in relation to physiological status (Yang and Hoffman 1984).

In many species exogenous ethylene can also accelerate floral senescence. Ethylene is produced by many plant tissues (Gane, 1934) and other sources, including bacterial and fungal fermentation processes, and pyrolysis of hydrocarbons, which releases ethylene as a component of air pollutants (Cape, 2003), all of which can thus affect the longevity of cut flowers in the horticultural supply chain. Ethylene is biologically active at very low concentrations ($\text{nl-}\mu\text{l l}^{-1}$), but there are significant differences in ethylene sensitivity between species and even cultivars of the same species (Serek et al., 2006b; Scariot et al., 2008). A detailed classification of flowers based on ethylene sensitiveness is reported by van Doorn (2001).

1.1.2 Plant species: sensitivity and effects

Responses to ethylene vary widely according to the species (Reid and Wu, 1992) although they are often consistent within either families or subfamilies (van Doorn, 2001). Ethylene-sensitive species include a number of important cut flowers. For example petals of orchids (*Phalaenopsis*), *Hibiscus* (Çelikel and Reid, 2002), and carnation (*Diathus caryophyllus*) (Serek et al., 1995a,b) wilt in response to ethylene. In other species, such as *Antirrhinum majus*, *Rosa hybrida* (Serek et al., 1995a), and

wax flower (*Chamelaucium uncinatum*) (Macnish et al., 2000), ethylene induces petal or flower abscission.

Ethylene sensitive flowers can be classified into three types (Kumar et al., 2008). First, those like carnation and petunia where senescence is regulated by an increased amount of ethylene production either with ageing or following pollination (Serek et al., 1995a). Second, like cyclamen, which only become sensitive to ethylene and produce increased amounts of the hormone when they are pollinated (Halevy et al., 1984). Third, like rose, which are sensitive to ethylene upon flower bud opening but do not produce elevated amounts of ethylene as they age (Kumar et al., 2008).

As well as accelerating petal senescence and deterioration, ethylene (either endogenous or from an external source) can induce other undesirable physiological disorders to vegetative and flowering organs during postharvest storage of cut flowers both in monocotyledons and dicotyledons including pathogen susceptibility (McKenzie and Lovell, 1992; van Doorn, 2001). For example, *Botrytis cinerea* is one of the most significant postharvest fungal pathogens causing losses in ornamental plants. Disease caused by this fungus has been shown to be enhanced by the presence of ethylene in rose and carnation (Elad, 1988; Seglie et al., 2012). However, depending on the type of pathogen and plant species, the role of ethylene can be dramatically different. Indeed plants deficient in ethylene signaling may show either increased susceptibility or increased resistance (Elad, 1988).

Thus data on ethylene sensitivity of cut flower species is important for predicting effects of exposure during the supply chain such as mixed storage and transport of flowers with fruit species. It is also needed to evaluate the appropriateness of treatments to reduce ethylene production or exposure and to inform breeding programs aimed at improving flower vase life.

1.2 Ethylene control strategies

Ethylene biosynthesis, perception, signal transduction are well-documented as well as is its regulation at biochemical and genetic levels (reviewed in Wang et al., 2002). This knowledge has been used to develop different strategies to reduce ethylene production or inhibit its action (either with new cultivars or vase-life treatments), and in turn to prolong flower postharvest performance.

Premature senescence and abscission caused by exposure to exogenous or endogenous ethylene can be mitigated in several ways (Figure 1) including, ethylene biosynthesis inhibitors, ethylene action inhibitors and ethylene removal technologies (reviewed in Martínez-Romero et al., 2007). Genetic modification is also a very effective way of controlling ethylene synthesis and perception. Attempts to obtain plants with both reduced endogenous ethylene biosynthesis or a reduced ethylene sensitivity have been reviewed by Serek et al. (2006b).

1.2.1 Genetic strategies

Changes in gene expression during petal senescence have been studied through transcriptomics of a number of model flowers (e.g., *Petunia*, *Arabidopsis*) and cut flower species (e.g., *Alstroemeria*, *Dianthus*, *Iris*, *Sandersonia*) (Rogers, 2013). In species where petal senescence is ethylene-sensitive groups of genes can be identified that are ethylene regulated, comprising transcription factors, genes encoding for enzymes in the biosynthetic pathway for ethylene production, ethylene receptors and ethylene signalling and responsive genes (Rogers 2013).

Ethylene biosynthesis is primarily regulated by 1-aminocyclopropane-1-carboxylic acid (ACC) synthase (ACS) and ACC oxidase (ACO) and an early success by the company Florigene in delaying carnation floral senescence was through antisense down-regulation of ACO (Savin et al., 1995). This success was closely followed by down-regulation of ACO in other flower species such as begonia (Einset and Kopperud, 1995) and torenia (Aida et al., 1998). Down-regulation of the ACS gene in carnation also reduced ethylene production (Kiss et al., 2000). Use of antisense sequences in *Petunia* for ACO and ACS, derived heterologously from broccoli also delayed floral senescence (Huang et al., 2007) showing that the approach can be used more broadly. However, these strategies have no effect when flowers are exposed to exogenous ethylene, as can occur during transit and marketing.

A more effective approach to protecting flowers from exogenous ethylene in the supply chain is therefore to focus on ethylene perception. Ethylene perception occurs through a well-conserved signalling pathway and the receptor is encoded by a family of five genes: *ETR1*, *ETR2*, *EIN4*, *ERS1* and *ERS2* (Yoo et al., 2009). Again an early discovery was that expression of a mutated *ETR1* gene from *Arabidopsis* (*etr1-1*) disrupts ethylene signalling in a wide range of heterologous species (Bleecker et al.,

198 1988; Wilkinson et al., 1997), making it an extremely useful tool (Binder, 2008, Serek
199 et al., 2006a). It has been used successfully in a range of ornamental species to delay
200 floral senescence including *Petunia* (Clevenger et al., 2004; Clark et al., 1999a;
201 Gubrium et al., 2000; Wilkinson et al., 1997), *Dianthus* (Bovy et al., 1999), *Campanula*
202 (Sriskandarajah et al., 2007) and *Kalanchoe* (Sanikhani et al., 2008). Other genes in
203 the ethylene signalling pathway such as *EIN2*, which is down-stream of the receptor,
204 have also been down-regulated in ornamental species such as *Petunia* (Shibuya et al.,
205 2004) resulting in delayed senescence.

206 However, as discussed above, ethylene affects a wide range of developmental
207 processes and physiological responses in the plant, thus a down-regulation of ethylene
208 responses throughout the plant can have undesired effects such as root formation
209 (Clark et al., 1999b), disease susceptibility (Shaw et al., 2002) and seed germination
210 (Clevenger et al., 2004) which in turn affect production. Therefore this strategy is most
211 effective when expression of the *etr1-1* mutant gene is driven by a flower specific
212 promoter derived from e.g the *Petunia* MADS box gene CBM2 (Baudinette et al., 2000)
213 or *fbp1* from *Petunia hybrida* (Raffeiner et al., 2009). This latter promoter was used
214 successfully to delay senescence, and shown to be specific for buds, petals or stamens
215 in transgenic *Dianthus*, *Campanula* and *Kalanchoe* (Bovy et al., 1999; Sanikhani et al.,
216 2008; Sriskandarajah et al., 2007). Ethylene sensitivity to 1µl/l ethylene was
217 completely abolished in *Kalanchoe* (Sanikhani et al., 2008) and in both *Kalanchoe* and
218 *Campanula* (Sriskandarajah et al., 2007) some lines were tolerant to levels of 2µl/l
219 ethylene. Crucially plants were otherwise phenotypically normal in all three species.
220 Alternative pathways for reducing ethylene sensitivity have also been tested. A recent
221 study by Christensen and Müller (2009) demonstrated that expression of *rol* genes can
222 also enhance postharvest performance and increase ethylene tolerance in transgenic
223 *Kalanchoe blossfeldiana*, even though the mechanisms involved are presently
224 unknown. Possible mechanisms are via an alteration of hormone homeostasis and/or
225 sugar metabolism and transport.

226 Although these approaches appear to be successful, there has been a lack of
227 commercialisation in ornamentals and only very few transgenic lines have been
228 commercialised (Chandler and Sanchez, 2012). One of the barriers is that while there
229 are hundreds of ornamental cut flower species and thousands of varieties, only about
230 fifty ornamental species are transformable (Chandler and Sanchez, 2012). A further

barrier is ascribed to the cost and complexity of the regulatory process and lack of harmonisation of the regulations across different world markets. Furthermore, despite being the largest market for ornamentals, the European regulatory environment is one of the most stringent. Alternative strategies are also therefore still required.

1.2.2 Environmental strategies

In many situations, considerable ethylene emission occurs throughout the horticultural distribution chain, such as in producer or market refrigerators and storage chambers, inside packaging, and during transportation (Martínez-Romero et al., 2007). This ethylene comes from normal emission from plant organs or external sources, such as micro organism metabolism and pyrolysis of hydrocarbons in internal combustion engines (Cape, 2003; Chang and Bleecker, 2004).

A first key approach is to reduce exposure to exogenous ethylene e.g. by avoiding mixed loads of ethylene sensitive and producer species). However, exogenous and endogenous ethylene exert similar effects, thus, in order to avoid detrimental effects on cut flower quality, its detection and removal is advisable. Ethylene levels as low as 20 $\mu\text{l l}^{-1}$ (ppm) inside conservation chambers are enough to trigger unwanted ripening processes of climacteric fruits (Ivanov et al., 2005). In fact air concentrations higher than 0.100 $\mu\text{l l}^{-1}$ can accelerate ripening and senescence processes, inducing important loss of quality (Wills and Warton, 2000). This leads to a reduction in shelf-life, in a wide range of other commodities (Wills et al., 2001), as well as in cut flowers (Reid and Jiang, 2012). Consequently lower concentrations (0.100-0.015 $\mu\text{l l}^{-1}$) have been recommended in processing and storage areas (Wills and Warton, 2000).

To reduce ethylene levels, three main approaches can be taken: removal. oxidation or absorption often used in combination. Reduced temperature is also useful: in cut flowers which tolerate low temperature (Cevallos, and Reid. 2001) including snapdragon (Çelikel et al., 2010), rose (Çelikel and Reid, 2005) and Asteraceae such as gerbera and sunflower (Çelikel, and Reid. 2002), refrigerated storage is beneficial in conservation and transport, since ethylene production and sensitivity are greatly reduced at low temperatures. Temperatures of 0 to 1 °C (32 to 33.8 °F) and 95 to 99% RH are the recommended conditions for these cut flowers and forced air cooling is the common method for pre-cooling products prior to storage (Reid and Jiang, 2012).

Adequate ventilation of warehouses with fresh air has been classically used to remove ethylene for storing climacteric vegetables, fruits and cut flowers, however this procedure is not practicable in sealed environments (e.g. controlled atmosphere or some packaging formats) or where a precise control is required. Furthermore this method results in significant energy losses by increasing the temperature and lowering the humidity. Therefore, most commercial control systems have relied for a long time on both ventilation (often periodic) and ethylene adsorption/oxidation, using materials with suitable adsorption properties, in terms of pore structure (magnitude and distribution of pores) surface chemistry (type and quality of surface-bound functional groups), molecular sieving and oxidation capacity (Martínez-Romero et al., 2007).

Based on these mechanisms, a number of options are available commercially. These include membranes for filtration, small sachets inside the packages, enriched polyethylene films for modified atmosphere, including zeolites (Suslow, 1997; Limtrakul et al., 2001) and activated carbon (Choi et al., 2003; Bailén et al., 2006), as adsorbers. The efficiency of activated carbon as an adsorber is dependent on a wide range of physical and chemical properties as well as the material formulation, granular, powdered or fibre (Aygün et al., 2003). Martínez-Romero et al. (2007) found that the best results in terms of the rate of absorption of applied ethylene were obtained with granular (80%), followed by powdered (70%) and fibre (40%) carbon. However, adsorption techniques on their own only transfer the ethylene to another phase (the solid adsorber matrix), rather than destroying it, and do not guarantee its total elimination.

Another strategy is oxidation. Inert matrices (e.g. alumina or silica gel) impregnated with potassium permanganate (KMnO_4), can be used as oxidising agents (Terry et al., 2007). However, performance of KMnO_4 depends on the percentage of active agent per matrix weight (usually 4 to 6%) and surface area of the substrate (Poças et al., 2008). In addition, in common with most of the ethylene scavengers, KMnO_4 has limited long-term efficacy in environments with high relative humidity (RH) (e.g. cold chambers, packaging, etc.) (Terry et al., 2007). Ozone (O_3) is an alternative gaseous oxidant, with good solubility in water and reactivity. Ozone acts as a powerful, residue-free ethylene oxidant and microbial disinfectant, which does not impair product appearance, texture, or scent. However it is highly unstable and decomposes easily into O_2 (Dickson et al., 1992). Furthermore, even though it has been listed as a GRAS

(generally recognized as safe) material by the US Food and Drug Administration (FDA), its application is strictly regulated (Mahapatra et al., 2005).

The combination of an adsorbent with an oxidizer or catalyst (chemi-adsorption) enhances the efficacy of the two single strategies. Indeed, the use of some catalysts (palladium Pd, titanium Ti, copper Cu, rhodium Rh and cobalt Co) have also been shown to be effective in ethylene removal, by oxidising it to CO₂ and H₂O, even at low temperature and high RH (Conte et al., 1992; Maneerat et al., 2003). For example, results obtained by combining activated carbon with Pd have been far superior to KMnO₄-based scavengers at room temperature (20 °C) (Bailén et al., 2007; Terry et al., 2007). Pd fixed on activated carbon increased the efficiency of ethylene adsorption compared to activated carbon alone, even at low concentration (1% in weight), making this strategy sustainable for practical applications in common packaging and modified atmosphere packaging (MAP), despite the high cost of Pd (Martínez-Romero et al., 2007). However, this kind of system has several disadvantages, including the large quantity of adsorbent + catalyst required (due to adsorption of other environmental gases and the subsequent loss of efficacy over time), the requirement to reposition the material, and non-continuous operation (since regeneration of the adsorbent is necessary) (Martínez-Romero et al., 2009).

A refinement to the adsorbent + catalyst strategy that can be used to remove ethylene continuously has been developed based on activated carbon-1% Pd and the application of short heat pulses (Martínez-Romero et al., 2009). This system allows an increase in the rate of ethylene adsorption and oxidation (96-99% at 150-200 °C) and the elimination of deposits of other gases on the activated carbon, avoiding system saturation (auto-regeneration). It thus compares favourably to other non heated adsorbent-catalyst systems, with low CO₂ accumulation and without affecting the temperature of the storage environment. Silver (Ag) ions also appear attractive as a catalyst, because of their photoactivity, photocatalysis, and antibacterial activity (Verykios et al., 1980).

In summary, ventilation and air temperature control are commonly used during postharvest storage and transport of most cut flowers, together with adsorbers or oxidizers, while “ozonators” and catalytic degradation reactors are less widely used. However, recent advances in technology promise to expand the use of catalytic

degradation in ethylene control in the floriculture industry (e.g. the carbon-heat hybrid ethylene scrubber; Martínez-Romero et al., 2009).

1.2.3 Chemical strategies

Use of ethylene biosynthesis inhibitors leads to a reduction in endogenous ethylene levels in the plant. These include cobalt ions (Lau and Yang 1976), aminooxyacetic acid (AOA) (Baker et al., 1982), aminoethoxyvinylglycine (AVG) (Baker et al., 1977; Wang et al., 1977), and methoxyvinylglycine (MVG) (Reid et al., 1992).

AVG and MVG are difficult to prepare and, thus, too expensive for practical use. Studies with AOA also indicated toxicological risks. Additionally, phytotoxicity is often a problem with these compounds. Therefore, new oxime ether derivatives of AOA have been recently proposed, including ethyl 4-[[2-[[[(1-phenylmethylidene)amino]oxy]acetyl]oxy] butanoate was especially which is found to be more effective than AOA, (Zeng et al., 2012). However, these chemicals are only effective against the action of ethylene produced by the flower itself, and have no effect when flowers are exposed to exogenous ethylene, as can occur during transit and marketing. Therefore, their use is valuable for studies of ethylene biosynthesis, but they are unlikely to play an important role in horticultural practice.

More common treatments are the use of inhibitors of flower ethylene responses. For a vast number of ornamental species, blocking the plant's response to ethylene via a chemical approach is an efficient strategy to enhance the longevity of the flowers (Serek et al. 2006a).

Ethylene action inhibitors interact with ethylene receptors and modulate ethylene responses. These include silver thiosulfate (STS) (Veen, 1979), 2,5-norbornadiene (2,5-NBD) (Sisler et al., 1983; Wang and Woodson, 1989), diazocyclopentadiene (DACP) (Blankenship and Sisler, 1993; Sisler et al., 1993; Serek et al., 1994) and 1-methylcyclopropene (1-MCP) (Serek et al., 1995b, 2006a). STS is a convenient ethylene inhibitor and has been widely used in commercial practice for a number of horticultural commodities (Veen, 1983). However, the use of silver raises environmental concerns, mainly related to disposal issues (Sisler et al., 1997; Marambio-Jones and Hock 2010). 2,5-NBD has a very disagreeable odour and requires continuous exposure to be effective, therefore it has very limited potential for

commercial use (Sisler et al., 1990). Similarly, instability and explosive characteristics of DACP make it an unlikely candidate for commercial use (Serek et al., 2006b).

1-MCP was the first patented non-toxic ethylene action inhibitor (Sisler and Blankenship, 1996). 1-MCP treatment conditions and effects on floricultural crops have been reviewed by Blankenship and Dole (2003). Its high efficacy has been well documented in a range of ornamental species and it is now widely used commercially under the trade name of EthylBloc® and SmartFresh™ (Serek et al., 2006b). However, the gaseous nature of 1-MCP leads to difficulties with its use due to three key factors: (i) plant material must be kept in enclosed areas to prevent gas leakage, (ii) the effect of 1-MCP can be transitory in some plants, depending on the species, the concentrations, and lighting (Sisler et al., 1996a, b; Blankenship and Dole 2003; Kebenei et al., 2003; Feng et al., 2004; Apelbaum et al., 2008), thus some ornamentals require continuous or repeated applications, (Serek and Sisler, 2005; Serek et al., 2006b) and (iii) and the action of commercial formulations of 1-MCP appears to be strongly reduced by treatment temperature (0–5°C) and by the presence of exogenous ethylene (Seglie et al., 2011a; Çelikel and Reid, 2002; Reid and Çelikel, 2008). Furthermore, many conventional 1-MCP delivery vehicles, such as cyclopropenes and cyclodextrins, have low preservative efficiency and, consequently, require high concentrations of active ingredients to be effective. These levels may induce side effects due to the high input levels (Sisler et al., 1996a, b, 1999). Advances have occurred to counter some of these limitations by developing 1-MCP-based compounds that can be applied in non-volatile formulations. Different cyclopropene salt compounds such as N,N-dipropyl(1-cyclopropenylmethyl)amine (DPCA) have been recently synthesized (Sisler et al., 2009) and used to protect several ornamentals against ethylene (Seglie et al., 2010). Cyclopropene salt compounds differ amongst each other in their chemical structure, but they all have a methyl group in the 1-position, onto which an amine is substituted. Such compounds can be used as a gas in a confined space or as a salt in open spaces. Moreover, recently, the company Floralife (Walterboro, SC) has released a novel treatment system 1-MCP sachets resembling tea bags. The bags are dipped in water just before being placed within a packed box; the water diffuses through the bag, and the 1-MCP in it is released into the air within the box. Preliminary experiments have shown this technique to be quite effective (Reid and Çelikel, 2008).

2. Nanotechnology for ethylene control

Nanotechnology can be defined as the design, characterization, production, and application of structures, devices, and systems by controlling the shape and size at the nanometer scale (Mousavi and Rezaei, 2011). Nanotechnology exploits the particular characteristics of nanoparticles (structures of 1 to 100 nm dimensions) and can be a very useful technology in a wide range of branches in science and industry. Understanding and controlling matter at the nanoscale interests researchers in the sciences, medicine, agriculture, and industry because a material's properties at the nanoscale can be very different from those at a larger scale (Yadollahi et al., 2010). Nanotechnology is widely employed in the agriculture and food industry, with many applications at all stages of product production, processing, storing, packaging and transport (Mousavi and Rezaei, 2011). Uses of nanotechnology aim to increase production and decrease postharvest wastage. Nanoparticles and nanoporous materials can be used to carry ethylene action inhibitors, control growth and development of microorganisms and introduce a new generation of packaging coverage that controls gases and harmful UV rays while increasing strength, quality and packaging appearance (Yadollahi et al., 2010). Application in the floriculture industry is still limited, nevertheless, a recent increase in nanotechnology research indicates a promising future for this technology throughout the supply chain (Figure 2). Recent results on the use of nanotechnology *sensu lato* for cut flower vase life improvement, focusing on ethylene control strategies, is discussed below.

2.1 Nanotechnology for ethylene detection and removal in the postharvest environment

2.1.1 Sensors using nanoparticles for the detection of ethylene

Ethylene gas sensors are used to detect and monitor the concentration of the gas in the environment. This can be aimed to prevent exposure of fruits and vegetables to detrimental levels of ethylene.

The most common nano-material used for detection in ethylene sensors is tin dioxide (stannic oxide, SnO₂) (Ivanov et al., 2005; Agarwal et al., 2012), others are tungsten

trioxide (WO_3 , Pitcher et al., 2003), palladium (Pd, Pietrucha and Lalevic, 1988), platinum (Pt, Winquist and Lundström, 1987), titanium dioxide (TiO_2 , Zhang et al., 2002), and zinc oxide (ZnO , Kang et al., 2004).

In more sophisticated versions, WO_3 - SnO_2 binary oxide, with uniform distribution of nano- WO_3 within a SnO_2 particle-based material, has been developed successfully (Pimtong-Ngam et al., 2007). Similarly, nano-Au/ Co_3O_4 , with gold catalyst nanoparticles dispersed on a nano- Co_3O_4 support surface, showed great potential, particularly for indoor environmental control of ethylene traces (Li et al., 2008). Most of these materials are used in resistor-based devices, where their conductivity increases or decreases as an effect of the exposure to different ethylene concentrations.

The usual techniques used to construct the sensing layer (e.g. ceramic paste, thick film printing, sol gel) require high-temperature heating and complex material mixing techniques. Furthermore, ethylene detection also requires expensive and complex methods such as quantum-cascade laser (Weidmann et al., 2004), gas chromatography (Butrym and Hartman, 1998), photoluminescence (Burstyn et al., 2005), and chemiluminescence (Nelson et al., 2000). Moreover, since metal oxide sensors are responsive to a wide spectrum of toxic and combustible gases, their selectivity needs to be improved. In this respect, multi-sensor arrays, including different metal oxides as sensing elements with partially overlapping sensitivities, as well as a modulated working temperature of the sensor, which alters the kinetics of adsorption and reaction at the sensor surface, allow significant improvements to the problem of selectivity (Ivanov et al., 2005). However, the problem of measuring ethylene levels continuously during storage of climacteric fruits or other fresh produce is critical because ethylene detectors are bulky and expensive (Agarwal et al., 2012; Cristescu et al., 2012).

A reversible chemioresistive sensor able to detect with high selectivity sub-ppm concentrations of ethylene and simply to be prepared from commercially available materials, has been recently proposed by Birgit et al. (2012).

Gas sensors containing nanostructures such as nanowires, e.g. the electronic detectors called electronic nose or e-nose, identify the odorant mimicking natural olfaction and estimate its concentration (Gardner and Bartlett, 1999). Sensors based on e-nose technology allow detection of the presence of ethylene in food products, because of contamination or spoilage (Valdés et al., 2009). Information from e-noses

on fruit physiological states, based on changes in released volatiles, can be applied to retard the ripening process through exposure of the fruit to inhibitors (such as cyclopropene compounds as ethylene-receptor blockers) at the appropriate time, adjustments in storage conditions to preclude ethylene accumulation, and removal of bruised or damaged fruits, over-producing ethylene (Wilson and Baietto, 2009). Nanomaterial-based sensors are widely applied in post harvest management of fruits (e.g. climacteric fruits like apples and peaches) and in the food industry (e.g. packaging of vegetables) (Cristescu et al., 2012). Nanosensors could therefore also help to prolong vase life of cut flowers, by enabling monitoring of ethylene concentrations in storage rooms of large growers and wholesale markets. However, a cost-benefit analysis is necessary to evaluate if this extra cost would be compensated by the extension of cut flower vase life in the different flower species and the specific market context. In addition, it has to be taken into account that monitoring ethylene levels in the supply chain would be useful only if the integrated ethylene exposure can be calculated and suitable data on the specific sensitivity of flowers to different levels of ethylene are available. In this respect, further research is needed in order to clarify the mechanisms of response to ethylene in the different plant species (reaction to a threshold value or an integral amount of ethylene). Furthermore, differences in sensitivity between species and even between varieties means that a very sophisticated system would be required which may not ultimately be cost-effective and may have limited applicability with mixed batches.

2.1.2 Nanocomposites and nanocatalyst for ethylene removal and photodegradation

Loss of quality and freshness of plant products during the time required for commercialization and consumption can be contained by means of the right selection of materials and packaging technologies, able to maintain the desired atmosphere. In this respect, nanotechnology can provide effective scavengers with selective ability to remove different gases (e.g. oxygen, ethylene). In particular, inclusion of nano-scale fillers (e.g. Pd) within the matrix can make plastic films more impermeable to ethylene (Neethirajan and Jayas, 2011). These nano-components help to create active packaging for fruits and vegetables, such as ethylene-scavenging bags, exhibiting barrier properties (Robinson and Morrison, 2010), or novel systems including nanoparticle-promoted absorbent matrices, such as Pd-enriched zeolite (Smith et al.,

2009) to include in classical packaging. Nanoparticulates work as small physical barriers to the movement of gas molecules, by obstructing the path of the gas through the material. Furthermore, they have a relatively larger surface area than larger fillers, which favours filler-matrix interactions and the performance of the composite, acting as nano-reinforcements. However, achieving optimal barrier and mechanical performance requires the correct concentration and an excellent dispersion of the nanoparticulates throughout the matrix.

The use of nano-fillers in polymer composites (mixtures of polymers with inorganic or organic additives) is leading to the development of polymer nanocomposites, which represent a radical alternative to conventional materials and offer extra benefits such as low density, transparency, good flow, better surface properties and recyclability (Sinha Ray and Okamoto, 2003).

The application of nanocomposites promises to expand the use of edible and biodegradable films for food packaging (Sinha Ray and Bousmina, 2005), which was strongly limited in the beginning because of the poor barrier properties and weak mechanical properties of natural polymers (Petersen et al., 1999). However, nowadays blending with other synthetic polymers or, less frequently, chemical adjustment allow their application to more severe circumstances (Rhim et al., 2013).

Some alternatives to active packaging (e.g. catalytic degradation) look very attractive as tools for ethylene control but they require expensive materials or techniques and still show a low cost effectiveness. Nano-catalytic degradation of ethylene, and other hazardous materials, is one of the most desirable and challenging goals in the development of environmentally friendly catalysts (Rickerby et al., 2000). It involves the actual destruction of organic contaminants rather than just the transfer from one phase to another. For practical ethylene removal, the best tested catalysts have been Pd and TiO₂ fixed on activated carbon (Rodríguez-Reinoso, 1997).

Titanium dioxide (TiO₂) has been the focus for light-activated photocatalytic degradation under ultraviolet (UV) irradiation, either from natural (sun) or artificial (lamps), because of its physical and chemical stability, low cost, availability and non-toxicity (Hussain et al., 2011). TiO₂ action is unaffected by relative humidity and is efficient at room temperature, however the constant need for UV light represents a limiting factor.

Silver (Ag) ions also show photoactivity, semiconductor photocatalysis, and antibacterial activity: nano-Ag absorbs and decomposes ethylene and can have more effective antibacterial activity than Ag (Hu and Fu, 2003). Thus, packaging films incorporating nano- Ag or TiO₂ (e.g. nanocomposite polyethylene film) contribute to preserve quality of fruits and vegetables, retarding senescence and decreasing microbial growth.

Application of nanocomposites and nanocatalysts in floriculture is still limited, however current advances in packaging materials and formats (reviewed by Rhim et al., 2013) and successful tests on photocatalytic reactor prototypes (Hussain et al., 2011; Li et al., 2008) demonstrate how these technologies are potentially economically viable for commercial application to cut flowers (Figure 2).

2.2 Nanoparticles and nanoporous materials for ethylene action inhibition

Recent advances in nanotechnology demonstrate the increased attention that is now being paid to the supramolecular assembly of simple components. The design of new biomaterials based on nanoscale structural characteristics can be expected to provide many potential applications. Nano-sized colloidal carriers have recently been developed and proposed for drug delivery, since their use can solubilise poorly water-soluble active principles and provide prolonged release, as well as improving their bioavailability and in some cases modifying the kinetic parameters (Cavalli et al., 2006). They can also protect active components from degradation. Among colloidal carriers, nanoparticles have in particular been described as a new technological approach (Cavalli et al., 2006).

Nanometer-sized silver (Ag⁺) particles (NS) are used in various applications as anti-microbials (Furno et al., 2004). NS have a high surface area to volume ratio and because of this property, they are considered to be more effective at preventing growth of bacteria and other microorganisms than the components of oxidation states of Ag (Furno et al., 2004). NS release Ag⁺ (Lok et al., 2007), which has been reported to interact with cytoplasmic components and nucleic acids, to inhibit respiratory chain enzymes and to interfere with membrane permeability (Russell and Hugo, 1994; Park et al., 2005). Use of NS is becoming increasingly widespread in medicine, fabrics, water purification and various other industrial and non-plant applications (Jain and

Pradeep, 2005; Dubas et al., 2006 and Chen and Schluesener, 2008). Their use as a pulse and vase solution treatment for cut flowers is relatively new. Studies have investigated the effectiveness of NS in extending the vase life of some cut flowers, including carnations, gerberas, acacias, and roses (Liu et al., 2009; Solgi et al., 2009; Lü et al., 2010; Liavali and Zarchini, 2012; Liu et al., 2012, Moradi et al., 2012, and Nazemi and Ramezani, 2013). The positive effect of a NS pulse treatment was attributed to inhibition of bacterial growth in the vase solution and at the cut stem ends. However, physiological activity of Ag^+ from NS is also a possibility. As with other cations (e.g. K^+ , Ca^{2+}), Ag^+ can have positive effects on plant stem hydraulic conductivity (van Ieperen, 2007). Also, Ag^+ is considered to be a general inhibitor of aquaporins (Niemietz and Tyerman, 2002), improving water relations (Lü et al., 2010). Besides antibacterial and acidic effects, NS could act as antiethylene agents. Ag^+ , generally applied as STS, is an effective ethylene action inhibitor (Beyer, 1976; Veen, 1979). Kim et al. (2005) suggested that NS acted as anti-ethylene agents on cut Asiatic hybrid *Lilium* 'Dream Land' and Oriental hybrid *Lilium* 'Sibera' (Lü et al., 2010).

Cyclodextrins (CDs) are nanometric biomaterials synthesised by enzymatic action on hydrolysed starch. They have a characteristic toroidal shape, which forms a well-defined truncated cone-shaped lipophilic cavity. CDs are able to include compounds whose geometry and polarity are compatible with that of their cavity. Furthermore, chemical modifications of CDs have been studied in an attempt to form inclusion complexes with hydrophilic or high-molecular-weight drugs too (Trotta et al., 2012).

One approach is to synthesize cross-linked CD-based polymers in order to prepare insoluble multifunctional CD derivatives. These polymers can be obtained by reacting native CDs with a cross-linking agent that, after reaction, exerts its own properties and influences the behaviour of the CD unit. Although insoluble cross-linked CD polymers were first reported a long time ago, the term cyclodextrin nanosponges (CD-NSs) was first used by Li and Ma (1998) to indicate a cross-linked β -CD with organic diisocyanates leading to an insoluble network that showed a very high inclusion constant with several organic pollutants. Generally speaking, CD-NSs are hyper-cross-linked CDs that can be obtained with α , β and γ CDs, either alone or as mixtures containing relevant amounts of linear dextrin, cross-linked with a suitable cross-linking agent. CD-NSs were initially used for removing persistent organic pollutants (POPs) in water purification (Li and Ma, 1999; Arkas et al., 2006). Then, further studies were

carried out in the preparation of cosmetics. Lately, medical and pharmaceutical applications have been of particular relevance, in which CD-NSs are used as carries for drug delivery (Trotta et al., 2012; Trotta, 2011).

Currently, evaluation of the potential for the use of CD-NSs in the field of agriculture appears an important research goal. CD-NSs hold a promising future in various applications such as enhanced product performance, improved thermal, physical, and chemical stability, and extended release and bioavailability.

In the postharvest context, CD-NSs (patented by Trotta et al., 2006) have been proposed as a delivery system capable of slowing the release of 1-MCP (Devecchi et al., 2009). These have the benefits of requiring reduced active ingredient dosages and reduced number of delivery times, as compared to the gaseous commercial product. In carnation, the inclusion of 1-MCP in a β -CD-NS structure has been shown to be effective not only in prolonging cut flower vase life (5 days more than gaseous 1-MCP; Seglie et al., 2011a; Seglie et al., 2011b) but also in controlling *Botrytis cinerea* damage (a 16% reduction in the development of grey mould; Seglie et al., 2012). The superior efficacy in improving postharvest performances of 1-MCP included in β -CD-NS has been seen also in a number of other ethylene sensitive species (*Anemone coronaria* L. multicolor, *Ranunculus asiaticus* L. 'Minou Abrown', *Helianthus annuus* L. 'SunrichOrange', *Rosa hybrida* L. 'Jupiter', *Paeonia lactiflora* Pall. 'Sarah Bernhardt', and *Papaver nudicaule* L. multicolor.) (Seglie et al., 2013). 1-MCP is a highly unstable and reactive gas that very quickly dimerizes even at room temperature. This dimer has no anti-ethylene activity. Most likely β -CD-NS stabilizes the included 1-MCP thus preserving its properties.

Therefore, 1-MCP included in β -CD-NS may be a promising user-friendly formulation, with low environmental impact, for prolonging the shelf life and controlling fungal diseases of cut flowers in the postharvest environment, although the mechanism of action needs further elucidation (Seglie et al., 2013). This new formulation appears moreover to have important economic implications: its application does not require an air-tight environment, allowing easier and faster open-space application, a major advantage for field production in ornamental nurseries/gardens. However, future commercial use of 1-MCP included in β -CD-NS will require more development to optimize chemical concentration and to evaluate this compound on an extended number of plant species in a range of environments.

3. Conclusions and Future prospects

Although a range of solutions exist currently to reduce the impact of ethylene on postharvest floral longevity through the supply chain, none currently meets all the requirements. However, recent progress in the development of nanotechnological strategies suggests that they have a lot to offer. Nanotechnologies could help to overcome postharvest quality and safety issues by developing user friendly green tools. Nano-scale systems could be applied to cut flowers for ethylene detection in the store environment (nano-metals based sensors) and along the distribution chain (nano-chip labels). They could also be used for ethylene removal (nano-metals for photocatalytic degradation in the warehouse or nanocomposites for scrubbing in active packaging). The use of new natural formulations (e.g. nanosponges) able to increase the bio-availability of the active ingredients has already been shown to enable a reduction in commonly applied concentrations of agrochemicals, helping to minimize the impact of agriculture on the environment and to reduce production costs. However, the efficiency and the economic benefit of applying each strategy to the flower industry needs to be evaluated in the different crop/market contexts.

Acknowledgment

This research was supported by the research project PRIN 2007 “Post-production physiology of ornamentals and quality maintenance technologies” founded by the Italian Ministry of University and Research. The authors contributed to this study in equal measure.

Literature

- Agarwal, M., Balachandran, M.D., Shrestha, S., Varahramyan, K., 2012. SnO₂ nanoparticle-based passive capacitive sensor for ethylene detection. J. Nanomater. Article ID 145406, 5 pages.
- Aida, R., Yoshida, T., Ichimura, K., Goto, R., Shibata, M., 1998. Extension of flower longevity in transgenic torenia plants incorporating ACC oxidase transgene. Plant Sci. 138, 91-101.

655 Apelbaum, A., Sisler, E.C., Feng, X., Goren, R., 2008. Assessment of the potency of
 656 1-substituted cyclopropenes to counteract ethylene-induced processes in plants.
 657 Plant Growth Regul. 55, 101-113.

658 Arkas, M., Allabashi, R., Tsiourvas, D., Mattausch, E.M., Perfler, R. 2006.
 659 Organic/Inorganic Hybrid Filters Based on Dendritic and Cyclodextrin
 660 "Nanosponges" for the Removal of Organic Pollutants from Water. *Environ. Sci.*
 661 *Technol.* 40 (8), 2771-2777.

662 Aygün, A., Yenisooy-Karaka, S., Duman, I., 2003. Production of granular activated
 663 carbon from fruit stones and nutshells and evaluation of their physical, chemical
 664 and adsorption properties. *Micropor. Mesopor. Mat.*, 66, 189-195.

665 Bailén, G., Gillén, F., Castillo, S., Serrano, M., Valero, D., Martínez-Romero, D., 2006.
 666 Use of activated carbon inside modified atmosphere packaging to maintain tomato
 667 fruit quality during cold storage. *J. Agric. Food Chem.* 54, 2229-2235.

668 Bailén, G., Guillén, F., Castillo, S., Zapata, P.J., Serrano, M., Valero, D., Martínez-
 669 Romero, D., 2007. Use of a palladium catalyst to improve the capacity of activated
 670 carbon to absorb ethylene, and its effect on tomato ripening. *Span. J. Agric. Res.*
 671 5, 579-586.

672 Baker, J.E., Anderson, J.D., Adams, D.O., Apelbaum, A., Lieberman, M., 1982.
 673 Biosynthesis of Ethylene from Methionine in Aminoethoxyvinylglycine-Resistant
 674 Avocado Tissue. *Plant Physiol.* January 69, 93-97.

675 Baker, J.E., Wang, C.Y., Lieberman, M., Hardenburg, R., 1977. Delay of senescence
 676 in carnations by rhizobitoxine analog and sodium benzoate. *HortSci.* 12, 38-39.

677 Baudinette, S.C., Stevenson, T.W., Savin, K.W., 2000. Isolation and characterisation
 678 of the carnation floral-specific MADS box gene, CMB2. *Plant Sci.* 155, 123-31.

679 Beyer, E.M., 1976. A potent inhibitor of ethylene action in plants. *Plant physiol.* 58(3),
 680 268-271.

681 Binder, B. M., 2008. The ethylene receptors: complex perception for a simple gas. *Plant*
 682 *Science* 175, 8-17.

683 Birgit, E., Schnorr, J.M., Swager, T.M., 2012. Selective detection of ethylene gas using
 684 carbon nanotube-based devices: utility in determination of fruit ripeness. *Chem.*
 685 *Int. Ed.* 51(23), 5752-5756.

686 Blankenship, S. M., Sisler, E.C., 1993. Response of apples to diazocyclopentadiene
 687 inhibition of ethylene binding. *Postharvest Biol. Technol.* 3(2), 95-101.

Blankenship, S.M., Dole, J.M., 2003. 1-Methylcyclopropene: a review. *Postharvest Biol. Technol.* 28, 1-25.

Bleecker, A.B., Estelle, M.A., Somerville, C., Kende, H., 1988. Insensitivity to ethylene conferred by a dominant mutation in *Arabidopsis thaliana*. *Science* 241, 1086-1089.

Bovy, A.G., Angenent, G.C., Dons, H.J., van Altvorst, A.C., 1999. Heterologous expression of the *Arabidopsis* *etr1-1* allele inhibits the senescence of carnation flowers. *Mol. Breed.* 5(4), 301-308.

Burstyn, J.N., Ellis, A.B., Green, O., Smith, N.A., 2005. Photoluminescent ethylene sensors. US Patent 20 050 031 985.

Butrym, E.D., Hartman, T.G., 1998. Determination of ethylene by adsorbent trapping and thermal desorption-gas chromatography, in: *Proceedings of the PittCon 1998*.

Cape, J. N., 2003. Effects of airborne volatile organic compounds on plants. *Environ. Pollut.* 122, 145-157.

Cavalli, R., Trotta, F., Tumiatti, W., 2006. Cyclodextrin-based nanosponges for drug delivery. *Incl. Phenom. Macrocycl. Chem.* 56, 209-213.

Çelikel, F.G., Cevallos, J.C., Reid, M.S., 2010. Temperature, ethylene and the post-harvest performance of cut snapdragons (*Antirrhinum majus*). *Scientia Hort.* 125, 429-433.

Çelikel, F.G., Reid, M.S., 2002. Postharvest handling of stock (*Matthiola incana*). *HortSci.* 37, 144-147.

Çelikel, F.G., Reid, M.S., 2005. Temperature and postharvest performance of rose (*Rosa hybrida* L. 'First Red') and gypsophila (*Gypsophila paniculata* L. 'Bristol Fairy') flowers. *Acta Hort.* 682, 1789-1794.

Cevallos, J.C. Reid, M.S. 2001. Effect of dry and wet storage at different temperatures on the vase life of cut flowers. *Hort. Technol.* 11, 199-202.

Chandler, S.F., Sanchez, C., 2012. Genetic modification; the development of transgenic ornamental plant varieties. *Plant Biotech. J.* 10, 891-903.

Chang, C., Bleecker, A.B., 2004. Ethylene biology. More than a gas. *Plant Physiol.* 136, 2895-2899.

Chen, X., Schluesener, H.J., 2008. Nanosilver: a nanoparticle in medical application. *Toxicol. Lett.* 176, 1-12

- Choi, B.U., Choi, D.K., Lee, Y.W., Lee, B.K., 2003. Adsorption equilibria of methane, ethane, ethylene, nitrogen, and hydrogen onto activated carbon. J. Chem. Eng. Data 48, 603-607.
- Christensen, B., Müller, R., 2009. *Kalanchoe blossfeldiana* transformed with rol-genes exhibits improved postharvest performance and increased ethylene tolerance. Postharvest Biol. Technol. 51(3), 399-406.
- Clark, D.G., Klee, H.J., Barrett, J.E., Nell, T.A., 1999a. Horticultural performance of ethylene insensitive petunias. in: Kanellis, A.K., Chang, C., Klee, H., Bleecker, A.B., Pech J.C., Grierson, D., (Eds.), Biology and Biotechnology of the Plant Hormone Ethylene II, Springer, Netherlands, pp. 357-363.
- Clark, D.G., Gubrium, E.K., Barrett, J.E., Nell, T.A., Klee, H.J., 1999b. Root Formation in Ethylene-Insensitive Plants. Plant Physiol. 121, 53-60.
- Clevenger, D.J., Barrett, J.E., Klee, H.J., Clark, D.G., 2004. Factors affecting seed production in transgenic ethylene-insensitive petunias. J. Am. Soc. Hort. Sci. 129, 401-406.
- Conte, J., El-Blidi, A., Rigal, L., Torres, L., 1992. Ethylene removal in fruit storage rooms: a catalytic oxidation reactor at low temperature. J. Food Eng. 15, 313-329.
- Cristescu, S.M., Mandon, J., Arslanov, D., De Pessemier, J., Hermans, C., Harren Frans, J.M., 2012. Current methods for detecting ethylene in plants. Invited Review. Ann. of Bot., doi:10.1093/aob/mcs259, available online at www.aob.oxfordjournals.org
- Devecchi, M., Trotta, F., Seglie, L., Kim, Y.J., Lava, C., Dolci, M., Scariot, V., 2009. Effects of anti-ethylene compounds included in nanosponges in improving the postharvest longevity of carnation (*Dianthus caryophyllus*) and buttercup (*Ranunculus asiaticus*) cut flowers. Acta Hort. 847, 237-244.
- Dickson, R.G., Law, S.E., Kays, S.J., Eiteman, M.A., 1992. Abatement of ethylene by ozone treatment in controlled atmosphere storage of fruits and vegetables. Proc. International Winter Meeting, Am. Soc. Agric. Engin. 1-9.
- Dubas, S.T., Kumlangdudsana, P., Potiyaraj, P., 2006. Layer-by-layer deposition of antimicrobial silver nanoparticles on textile fibers. Colloids Surf. A: Physicochem. Eng. Asp. 289(1), 105-109.
- Einset, J.W., Kopperud, C., 1995. Antisense ethylene genes for *Begonia* flowers. Acta Hort. 405, 190-6.

753 Elad, Y., 1988. Involvement of ethylene in the disease caused by *Botrytis cinerea* on
754 rose and carnation flowers and the possibility of control. *Annals of Appl. Biol.* 113
755 (3), 589-598.

756 Feng, X., Apelbaum, A., Sisler, E.C., Gore, R., 2004. Control of ethylene activity in
757 various plant systems by structural analogues of 1-methylcyclopropene. *Plant*
758 *Growth Regul.* 42, 29-38.

759 Furno, F., Morley, K.S., Wong, B., Sharp, B.L., Arnold, P.L., Howdle, S.M., Reid, H.J.,
760 2004. Silver nanoparticles and polymeric medical devices: a new approach to
761 prevention of infection?. *J. Antimicrob. Chemother.* 54(6), 1019-1024.

762 Gane, R., 1934. Production of ethylene by some ripening fruit. *Nature* 134, 1008.

763 Gardner, J.W., Bartlett, P.N., 1999. *Electronic Noses: Principles and Applications*, 1st
764 edn. Oxford University Press, Oxford.

765 Gubrium, E.K., Clevenger, D.J., Clark, D.G., Barrett, J.E., Nell, T.A., 2000.
766 Reproduction and horticultural performance of transgenic ethylene-insensitive
767 petunias. *J. Am. Soc. Hortic.Sci.* 125, 277-281.

768 Halevy, A.H., Whitehead, C.S., Kofranek, A.M., 1984. Does pollination induce corolla
769 abscission of cyclamen flowers by promoting ethylene production?. *Plant physiol.*
770 75(4), 1090-1093.

771 Hu, A.W., Fu, Z.H., 2003. Nano technology and its application in packaging and
772 packaging machinery. *Packag. Eng.* 24, 22-24.

773 Huang, L.C., Lai, U., Yang, S.F., Chu, M.J., Kuo, C.I., Tsai, M F., Sun, C.W., 2007.
774 Delayed flower senescence of *Petunia hybrida* plants transformed with antisense
775 broccoli ACC synthase and ACC oxidase genes. *Postharvest Biol. Technol.* 46(1),
776 47-53.

777 Hussain, M., Bensaid, S., Geobaldo, F., Saracco, G., Russo N., 2011. Photocatalytic
778 degradation of ethylene emitted by fruits with TiO₂ nanoparticles. *Ind. Eng. Chem.*
779 *Res.* 50, 2536-2543.

780 Ivanov, P., Llobet, E., Vergara, A., Stankova, M., Vilanova, X., Hubalek, J., Gracia, I.,
781 Cané, C., Correig, X., 2005. Towards a micro-system for monitoring ethylene in
782 warehouses. *Sens. Actuators B* 111-112, 63-70.

783 Jain, P., Pradeep, T., 2005. Potential of silver nanoparticle□coated polyurethane foam
784 as an antibacterial water filter. *Biotechnol. Bioengin.* 90(1), 59-63.

785 Kang, B.S., Kim, S., Ren, F., Ip, K., Heo, Y.W., Gila, B., Abernathy, C.R., Norton, D.P.,
786 Pearton, S.J., 2004. Detection of C₂H₄ using wide-bandgap semiconductor
787 sensors: AlGaIn/GaN MOS diodes and bulk ZnO schottky rectifiers. J.
788 Electrochem. Soc. 151(7), G468-G471.

789 Kebenei, Z., Sisler, E.C., Winkelmann, T., Serek, M., 2003. Efficacy of new inhibitors
790 of ethylene perception in improvement of display life of kalanchoë (*Kalanchoë*
791 *blossfeldiana* Poelln.) flowers. Postharvest Biol. Technol. 30(2), 169-176.

792 Kim, J.H., Lee, A.K., Suh, J.K., 2005. Effect of certain pre-treatment substances on
793 vase life and physiological character in *Lilium spp.* Acta Hort. 673, 307-314

794 Kiss, E., Veres, A., Galli, Z., Nagy, N., Tóth, E., Varga, Á., Hrazdina, G., Heszky, L.,
795 2000. Production of transgenic carnation with antisense ACS (*1-*
796 *aminocyclopropane-1-carboxylate synthase*) gene. Intl. J. Hortic. Sci. 6(4), 103-
797 107.

798 Kumar, N., Srivastava, G.C., Dixit, K., 2008. Flower bud opening and senescence in
799 roses (*Rosa hybrida* L.). Plant Growth Regul. 55(2), 81-99.

800 Lau, O.L., Yang, S.F., 1976. Inhibition of ethylene production by cobaltous ion. Plant
801 Physiol 58(1), 114-117.

802 Li, D., Ma, M., 1998. Cyclodextrin polymer separation materials. Patent WO 9822197.

803 Li, D., Ma, M., 1999. Nanoporous polymers: new nanosponge absorbent media. Filtr.
804 Separat. 36, 26-28.

805 Li, J., Ma, C., Xu, X., Yu, J., Hao, Z., Qiao, S., 2008. Efficient elimination of trace
806 ethylene over nano-gold catalyst under ambient conditions. Environ. Sci. Technol.,
807 42, 8947-8951.

808 Liavali, M.H., Zarchini, M., 2012. Effect of pre-treated chemicals on keeping quality and
809 vase life of cut rose (*Rosa hybrida* cv. 'Yellow Island'). J. Ornam. Hortic. Plants 2(2),
810 123-130.

811 Limtrakul, J., Nanok, T., Jungsuttiwong, S., Khongpracha, P., Truong, T.N., 2001.
812 Adsorption of insaturated hydrocarbons on zeolites: the effects of the zeolite
813 framework on adsorption properties of ethylene. Chem. Phys. Lett. 349, 161-166.

814 Liu, J., He, S., Zhang, Z., Cao, J., Petaio, L.V., He, S., Cheng, G., Joyce, D.C., 2009.
815 Nano- silver pulse treatments inhibit stem-end bacteria on cut gerbera cv. Ruikou
816 flowers. Postharvest Biol. Technol. 54, 59-62.

817 Liu, J., Ratnayake, K., Joyce, D.C., He, S., Zhang, Z., 2012. Effects of three different
818 nano-silver formulations on cut *Acacia holosericea* vase life. Postharvest Biol.
819 Technol. 66, 8-15

820 Lok, C.N., Ho, C.M., Chen, R., He, Q.Y., Yu, W.Y., Sun, H., Che, C.M., 2007. Silver
821 nanoparticles: partial oxidation and antibacterial activities. J. Biol. Inorg. Chem.
822 12(4), 527-534.

823 Lü, P., Cao, J., He, S., Liu, J., Li, H., Cheng, G., Ding, Y., Joyce, D.C., 2010. Nano-
824 silver pulse treatments improve water relations of cut rose cv. 'Movie Star' flowers.
825 Postharvest Biol. Technol. 57(3), 196-202.

826 Macnish, A.J., Joyce, D.C., Hofman, P.J., Simons, D.H., Reid, M.S., 2000. 1-
827 methylcyclopropene treatment efficacy in preventing ethylene perception in
828 banana fruit and grevillea and waxflowers. Aust. J. Exp. Agr. 40, 471-481.

829 Mahapatra, A.K., Muthukumarappan, K., Julson, J.L., 2005. Applications of ozone
830 bacteriocins and irradiation in food processing: a review. Crit. Rev. Food Sc. Nutr.
831 45, 447-461.

832 Maneerat, C., Hayata, Y., Egashira, N., Sakamoto, K., Hamai, Z., Kuroyanagi, M.,
833 2003. Photocatalytic reaction of TiO₂ to decompose ethylene in fruit and vegetable
834 storage. Trans. Am. Soc. of Agric. Eng. 46, 725-730.

835 Marambio-Jones, C., Hoek, E.M., 2010. A review of the antibacterial effects of silver
836 nanomaterials and potential implications for human health and the environment. J.
837 Nanopart. Res. 12(5), 1531-1551.

838 Martínez-Romero, D., Bailén, G., Serrano, M., Guillén, F., Valverde, J.M., Zapata, P.,
839 Castillo, S. Valero, D., 2007. Tools to maintain postharvest fruit and vegetable
840 quality through the inhibition of ethylene action: a review. Crit.Rev. Food Sci. Nutr.
841 47(6), 543-560.

842 Martínez-Romero, D., Guillén, F., Castillo, S., Zapata, P.J., Serrano, M., Valero, D.,
843 2009. Development of a carbon-heat hybrid ethylene scrubber for fresh
844 horticultural produce storage purposes. Postharvest Biol. Technol. 51, 200-205.

845 McKenzie, R.J., Lovell, P.H., 1992. Flower senescence in monocotyledons: A
846 taxonomic survey. New Zealand J. Crop and Hortic. Sci. 20 (1), 67-71.

847 Michailides, T.J.; Manganaris, G.A., 2009. Harvesting and handling effects on
848 postharvest decay. Stewart Postharvest Review 5 (2), 1-7.

849 Moradi, P., Afshari, H., Ebadi, A.G., 2012. The effect of benzyl adenine, nano silver, 8-
850 hydroxyquinolin sulfate, and sucrose on longevity improvement and some other
851 quality characteristics of *Dianthus* Cv. Cream Viana cut flower. Indian J. Sci.
852 Technol. 5(S3), 2459-2463.

853 Mousavi, S.R., Rezaei, M., 2011. Nanotechnology in agriculture and food production.
854 J. Appl. Environ. Biol. Sci. 1(10), 414-419.

855 Nazemi Rafi, Z., Ramezani, A., 2013. Vase life of cut rose cultivars 'Avalanche' and
856 'Fiesta' as affected by nano-silver and S-carvone treatments. S. Afr. J. Bot. 86, 68-
857 72.

858 Neethirajan, S., Jayas, D.S., 2011. Nanotechnology for the food and bioprocessing
859 industries. Review paper. Food Bioprocess Technol. 4, 39-47.

860 Nelson, B.N., Richard, R.V., Kanc, J.A., 2000. Ethylene monitoring and control system.
861 US Patent 6 105 416.

862 Niemietz, C.M., Tyerman, S.D., 2002. New potent inhibitors of aquaporins: silver and
863 gold compounds inhibit aquaporins of plant and human origin. Fed. Soc. Biochem.
864 Mol. Biol. Lett. 531, 443-447.

865 Park, S.H., Oh, S.G., Mun, J.Y., Han, S.S., 2005. Effects of silver nanoparticles on the
866 fluidity of bilayer in phospholipid liposome. Colloids Surf. B: Biointerfaces 44(2),
867 117-122.

868 Petersen, K., Nielsen, P.V., Bertelsen, G., Lawther, M., Olsen, M.B., Nilsson, N.H.,
869 1999. Potential of biobased materials for food packaging. Trends Food Sci.
870 Technol. 10, 52-68.

871 Pietrucha, B., Lalevic, B., 1988. Detection of hydrocarbon gases using PdMNOS
872 capacitors. Sens. Actuators 13(3), 275-286.

873 Pimtong-Ngam, Y., Jiemsirilers, S., Supothina, S., 2007. Preparation of tungsten
874 oxide-tin oxide nanocomposites and their ethylene sensing characteristics. Sens.
875 Actuat. A 139:7-11.

876 Pitcher, S., Thiele, J.A., Ren, H., Vetelino, J.F., 2003. Current/voltage characteristics
877 of a semiconductor metal oxide gas sensor. Sens. Actuators B 93(1-3), 454-462.

878 Poças, M.F., Delgado, T.F., Oliveira, F.A.R., 2008. Smart packaging technologies for
879 fruits and vegetables, in: Kerry, J., Butler, P. (Eds.), Smart Packaging Technologies
880 for Fast Moving Consumer Goods. John Wiley & Sons Ltd, Hoboken, NJ, USA pp.
881 151-166.

882 Raffener, B., Serek, M., Winkelmann, T., 2009. *Agrobacterium tumefaciens*-mediated
883 transformation of *Oncidium* and *Odontoglossum* orchid species with the ethylene
884 receptor mutant gene *etr1-1*. Plant Cell, Tissue and Organ Cult. 98(2), 125-134.

885 Reid, M.S., Çelikel, F.G., 2008. Use of 1-methylcyclopropene in ornamentals:
886 carnations as a model system for understanding mode of action. HortSci. 43, 95-
887 98.

888 Reid, M.S., Jiang, C.Z., 2012. Postharvest Biology and Technology of Cut Flowers and
889 Potted Plants, in: Janick, J. (Eds), Horticultural Reviews, Volume 40, First Edition.
890 John Wiley & Sons, Inc., Hoboken, NJ, USA, pp. 1-54.

891 Reid, M.S., Wu, M.J., 1992. Ethylene and flower senescence. Plant Growth Regul. 11,
892 37-43.

893 Rhim, J.W., Park, H.M., Hac, C.S., 2013. Bio-nanocomposites for food packaging
894 applications. Prog. in Polymer Sci.
895 <http://dx.doi.org/10.1016/j.progpolymsci.2013.05.008>, available online at
896 journalhomepage: www.elsevier.com/locate/ppolysci

897 Rickerby, D.G., Wätchter, N., Horrillo, M.C., Gutiérrez, J., Gràcia, I., Cané, C., 2000.
898 Structural and dimensional control in micromachined integrated solid state gas
899 sensors, Sens. Actuators B 69, 314-319.

900 Robinson, D.K.R., Morrison, M.J., 2010. Nanotechnologies for food packaging:
901 Reporting the science and technology research trends: Report for the Observatory
902 NANO. August 2010. www.observatorynano.eu.

903 Rodríguez-Reinoso, F., 1997. Activated carbon: preparation, structure,
904 characterization and applications, in: Marsh, H., Heintz, E.A., Rodriguez-Reinoso,
905 F. (Eds), Introduction to Carbon Technologies. Universidad de Alicante (Spain), pp.
906 35-92.

907 Rogers, H.J., 2013. From models to ornamentals: how is flower senescence
908 regulated? Plant Mol. Biol. 82(6), 563.

909 Russell, A.D., Hugo, W.B., 1994. Antimicrobial activity and action of silver. Prog. Med.
910 Chem. 31, 351-370.

911 Sanikhani, M., Mibus, H., Stummann, B.M., Serek, M., 2008. *Kalanchoe blossfeldiana*
912 plants expressing the Arabidopsis *etr1-1* allele show reduced ethylene sensitivity.
913 Plant cell Rep. 27(4), 729-737.

- Savin K. W., Baudinette S.C., Graham M.W., Michael M.Z., Nugent G.D., Lu C-Y, Chandler S.F., Cornish E.C., 1995. Antisense ACC oxidase RNA delays carnation petal. senescence. HortSci. 30 970-972.
- Scariot, V., Seglie, L., Caser, M., Devecchi, M., 2008. Evaluation of ethylene sensitivity and postharvest treatments to improve the vase life of four *Campanula* species. Eur. J. Hortic. Sci. 73(4), 166-170.
- Seglie, L., Devecchi, M., Trotta, F., Scariot, V., 2013. β -Cyclodextrin-based nanosponges improve 1-MCP efficacy in extending the postharvest quality of cut flowers. Sci. Hortic. 159, 162-165.
- Seglie, L., Martina, K., Devecchi, M., Roggero, C., Trotta, F., Scariot, V., 2011b. β -Cyclodextrin-based nanosponges as carriers for 1-MCP in extending the postharvest longevity of carnation cut flowers: an evaluation of different degrees of cross-linking. Plant Growth Regul. 65, 505-511.
- Seglie, L., Martina, K., Devecchi, M., Roggero, C., Trotta, F., Scariot, V., 2011a. The effects of 1-MCP in cyclodextrin-based nanosponges to improve the vase life of *Dianthus caryophyllus* cut flowers. Postharvest Biol. Technol. 59, 200-205.
- Seglie, L., Sisler, E.C., Mibus, H., Serek, M., 2010. Use of a non-volatile 1-MCP formulation, N, N-dipropyl (1-cyclopropenylmethyl) amine, for improvement of postharvest quality of ornamental crops. Postharvest Biol. Technol. 56(2), 117-122.
- Seglie, L., Spadaro, D., Trotta, F., Gullino, M.L., Devecchi, M., Scariot, V., 2012. Use of 1-Methylcyclopropene in cyclodextrin-based nanosponges to control grey mould caused by *Botrytis cinerea* on *Dianthus caryophyllus* cut flowers. Postharvest Biol. Technol. 64, 55-57.
- Serek, M., Sisler, E.C., 2005. Impact of 1-MCP on postharvest quality of ornamentals. APEC Symp. Quality Manag. Postharvest System Proc., 121-128.
- Serek, M., Sisler, E.C., Frello, S., Sriskandarajah, S., 2006b. Postharvest technologies for extending the shelf life of ornamental crops. Int. J. Postharvest Technol. Inn. 1, 69-75.
- Serek, M., Sisler, E.C., Reid, M.S., 1994. Novel gaseous ethylene binding inhibitor prevents ethylene effects in potted flowering plants. J. Am. Hort. Sci. 119, 1230-1233.
- Serek, M., Sisler, E.C., Reid, M.S., 1995a. Effects of 1-MCP on the vase life and ethylene response of cut flowers. Plant Growth Regul. 16, 93-97.

947 Serek, M., Sisler, E.C., Reid, M.S., 1995b. 1-methylcyclopropene, a novel gaseous
 948 inhibitor of ethylene action, improves the vase life of fruits, cut flowers and potted
 949 plants. *Acta Hort.* 394, 337-346.

950 Serek, M., Woltering, E.J., Sisler, E.C., Frello S., Sriskandarajah, S., 2006a. Controlling
 951 ethylene at the receptor level. *Biotechnol. Adv.* 24, 368-381.

952 Sharma, R.R., Alemwati, P., 2010. Natural products for postharvest decay control in
 953 horticultural produce: a review. *Stewart Postharvest Review* 6 (4), 1-9.

954 Shaw, J.F., Chen, H.H., Tsai, M.F., Kuo, C.I., Huan, L.C., 2002. Extended flower lon-
 955 gevity for *Petunia hybrida* plants transformed with boers, a mutated ERS gene of
 956 *Brassica oleracea*. *Mol Breed.* 9, 211-216.

957 Shibuya, K., Barry, K.G., Ciardi, J.A., Loucas, H.M., Underwood, B.A., Nourizadeh, S.,
 958 et al., 2004. The central role of PhEIN2 in ethyleneresponses throughout plant de-
 959 velopment in petunia. *Plant Physiol.* 136, 2900-2912.

960 Sinha Ray, S., Bousmina, M., 2005. Biodegradable polymers and their layered silicate
 961 nanocomposites: in greening the 21st century materials world. *Prog. Material Sci.*,
 962 50, 962-1079.

963 Sinha Ray, S., Okamoto, M., 2003. Polymer/layered silicate nanocomposites: a review
 964 from preparation to processing. *Progress Polym. Sci.* 28, 1539-1641.

965 Sisler, E.C., Blankenship, S., 1996. Methods of counteracting an ethylene response in
 966 plants. US Patent Number, 5518988.

967 Sisler, E.C., Blankenship, S.M., Fearn, J.C., Haynes, R., 1993. Effect of
 968 diazocyclopentadiene (DACP) on cut carnations, in: Pech, J.C., Latche, A.,
 969 Balague C. (Eds.), *Cellular and Molecular Aspects of the Plant Hormone Ethylene*,
 970 Kluwer Academic Publishers Dordrecht, The Netherlands, pp. 182-187.

971 Sisler, E.C., Blankenship, S.M., Guest, M., 1990. Competition of cyclooctenes and
 972 cyclooctadienes for ethylene binding and activity in plants. *Plant Growth Regul.*
 973 9(2), 157-164.

974 Sisler, E.C., Dupille E., Serek M., 1996a. Effect of 1-methylcyclopropene and
 975 methylenecyclopropane on ethylene binding and ethylene action on cut carnations.
 976 *Plant Growth Regul.* 18, 79-86.

977 Sisler, E.C., Goren, R., Apelbaum, A., Serek, M., 2009. The effect of dialkylamine
 978 compounds and related derivatives of 1-methylcyclopropene in counteracting
 979 ethylene responses in banana fruit. *Postharvest Biol. Technol.* 51, 43-48.

980 Sisler, E.C., Reid, M.S., Fujino, D.W., 1983. Investigation of the model of action of
 981 ethylene in carnation senescence. *Acta Hort.* 141, 229-234.

982 Sisler, E.C., Serek M., Dupille E., 1996b. Comparison of cyclopropene, 1-
 983 methylcyclopropene and 3,3-dimethylcyclopropene as ethylene antagonists in
 984 plants. *Plant Growth Regul.* 18, 169-174.

985 Sisler, E.C., Serek, M., 1997. Inhibitors of ethylene responses in plants at the receptor
 986 level: Recent developments. *Physiol. Plant.* 100, 577-582.

987 Sisler, E.C., Serek, M., Dupille, E., Goren, R., 1999. Inhibition of ethylene responses
 988 by 1-methylcyclopropene and 3-methylcyclopropene. *Plant Growth Regul.* 27, 105-
 989 111.

990 Smith, A.W.J., Poulston, S., Rowsell, L., 2009. A new palladium-based ethylene
 991 scavenger to control ethylene-induced ripening of climacteric fruit. *Platinum Metals*
 992 *Rev.*, 53, (3), 112-122.

993 Solgi, M., Kafi, M., Taghavi, T.S., Naderi, R., 2009. Essential oils and silver
 994 nanoparticles (SNP) as novel agents to extend vase life of gerbera (*Gerbera*
 995 *jamesonii* cv. 'Dune') flowers. *Postharvest Biol. Technol.* 53, 155-158.

996 Sriskandarajah, S., Mibus, H., Serek, M., 2007. Transgenic *Campanula carpatica*
 997 plants with reduced ethylene sensitivity. *Plant Cell Rep.* 26(6), 805-813.

998 Suslow, T., 1997. Performance of zeolite based products in ethylene removal. *Perish.*
 999 *Handl. Quarter.* 92, 32-33.

1000 Terry, L.A., Ilkenhans, T., Poulston, S., Rowsell, L., Smith, A.W.J., 2007. Development
 1001 of new palladium-promoted ethylene scavenger. *Postharvest Biol. Technol.* 45,
 1002 214-220.

1003 Toivonen, P.M.A, 2007. Fruit maturation and ripening and their relationship to quality.
 1004 *Stewart Postharvest Review* 3 (2), 1-5.

1005 Trotta, F., 2011. Cyclodextrin nanosponges and their applications, in: Bilensoy, E. (Ed.),
 1006 *Cyclodextrins in Pharmaceuticals, Cosmetics and Biomedicine: Current and Future*
 1007 *Industrial Applications.* John Wiley & Sons, Hoboken, NJ, USA, pp. 323-342.

1008 Trotta, F., Cavalli, R., Tumiatti, W., Zerbinati, O., Roggero, C., Vallero, R., 2006.
 1009 Ultrasoundassisted synthesis of cyclodextrin-based nanosponges. Patent
 1010 WO2006/002814.

1011 Trotta, F., Zanetti, M., Cavalli, R., 2012. Cyclodextrin-based nanosponges as drug
 1012 carriers. *Beilstein J. Org. Chem.* 8(1), 2091-2099.

1013 Valdés M.G., Valdés González, A.C., García Calzón, J.A., Díaz-García, M.E., 2009.
 1014 Analytical nanotechnology for food analysis - Review article. *Microchim. Acta* 166,
 1015 1-19.

1016 van Doorn, W.G., 2001. Categories of petal senescence and abscission: a re-
 1017 evaluation. *Ann. Bot.* 87, 447-456.

1018 van Doorn, W.G., Woltering, E.J., 2008. Physiology and molecular biology of petal
 1019 senescence. *J. Exp. Bot.* 59(3), 453-480.

1020 van Ieperen W., 2007. Ion-mediated changes of xylem hydraulic resistance in planta:
 1021 fact or fiction? *Trends Plant Sci.* 12, 137-142.

1022 Veen, H., 1979. Effects of silver on ethylene synthesis and action in cut carnations.
 1023 *Planta* 145, 467-470.

1024 Veen, H., 1983. Silver thiosulphate: An experimental tool in plant science. *Sci. Hortic.*
 1025 20 (3), 211-224

1026 Verykios, X.E., Stein, F.P., Coughlin, R.W., 1980. Oxidation of ethylene over silver -
 1027 adsorption, kinetics, catalyst. *Catalysis Reviews - Sci. and Engin.* 22(2), 197-234.

1028 Wang, C.Y., Baker, J.E., Hardenburg, R., Lieberman, M., 1977. Effects of two analogs
 1029 of rhizobitoxine sodium benzoate on senescence of snapdragons. *J. Am. Soc.*
 1030 *Hortic. Sci.* 102, 517-520.

1031 Wang, H., Woodson, W.R., 1989. Reversible inhibition of ethylene action and
 1032 interruption of petal senescence in carnation flowers by norbornadiene. *Plant*
 1033 *Physiol.* 89, 434-438.

1034 Wang, K.L.C., Li H., Ecker, J.R., 2002. Ethylene biosynthesis and signaling networks.
 1035 *Plant Cell* 14, S131-S151.

1036 Weidmann, D., Kosterev, A.A., Roller, C., Curl, R.F., Fraser, M.P., Tittel, F.K., 2004.
 1037 Monitoring of ethylene by a pulsed quantum cascade laser. *App. Opt.* 43(16), 3329-
 1038 3334.

1039 Wilkinson, J.Q., Lanahan, M.B., Clark, D.G., Bleecker, A.B., Chang, C., Meyerowitz,
 1040 E.M., Klee, H.J., 1997. A dominant mutant receptor from *Arabidopsis* confers
 1041 ethylene insensitivity in heterologous plants. *Nat. Biotechnol.* 15(5), 444-447.

1042 Wills, R.B.H., Warton, M.A., 2000. A new rating scale for ethylene action on postharvest
 1043 fruit and vegetables, in: Artés, F., Gil, M.I., Conesa, M.A. (Eds.), *Improving*
 1044 *Postharvest Technologies of Fruits, Vegetables and Ornamentals*. Institute
 1045 International of Refrigeration, Murcia, Spain, pp. 43-47.

1046 Wills, R.B.H., Warton, M.A., Mussa, D.M.D.N., Chew, L.P., 2001. Ripening of
1047 climacteric fruits initiated at low ethylene levels. *Aust. J. Exp. Agr.* 41, 89-92.

1048 Wilson A.D., Baietto, M., 2009. Applications and advances in electronic-nose
1049 technologies. Review article. *Sensors* (9), 5099-5148.

1050 Winquist, F., Lundström, I., 1987. Thin metal film-oxidesemiconductor structures with
1051 temperature-dependent sensitivity for unsaturated hydrocarbons. *Sens. Actuators*
1052 12 (3), 255-261.

1053 Yadollahi, A., Arzani, K., Khoshghalb, H., 2010. The role of nanotechnology in
1054 horticultural crops postharvest management. In: *Proceedings of Southeast Asia*
1055 *Symposium on Quality and Safety of Fresh and Fresh-Cut Produce. Acta Hortic.*
1056 875, pp. 49-56.

1057 Yang, S., Hoffman, F., 1984. Ethylene biosynthesis and its regulation in higher plants.
1058 *Ann. Rev. Physiol.* 35, 155-189.

1059 Yoo, S.D., Cho, Y., Sheen, J., 2009. Emerging connections in the ethylene signaling
1060 network. *Trends Plant Sci.* 14(5), 270-9.

1061 Zeng, Z., Jiang, H., Zhang, H., Jiang, Z., 2012. The synthesis of novel oxime ethers
1062 and their effects on the senescence of cut carnation flowers. *Res. Chem. Intermed.*
1063 38(2), 463-470.

1064 Zhang, R., Tejedor, M.I., Anderson, M.A., Paulose, M., Grimes, C.A., 2002. Ethylene
1065 detection using nanoporous PtTiO₂ coatings applied to magnetoelastic thick films.
1066 *Sens.* 2(8), 331-338.

1067

Figure 1 – Schematic view of ethylene control strategies in production and distribution chain of ethylene-sensitive plant species.

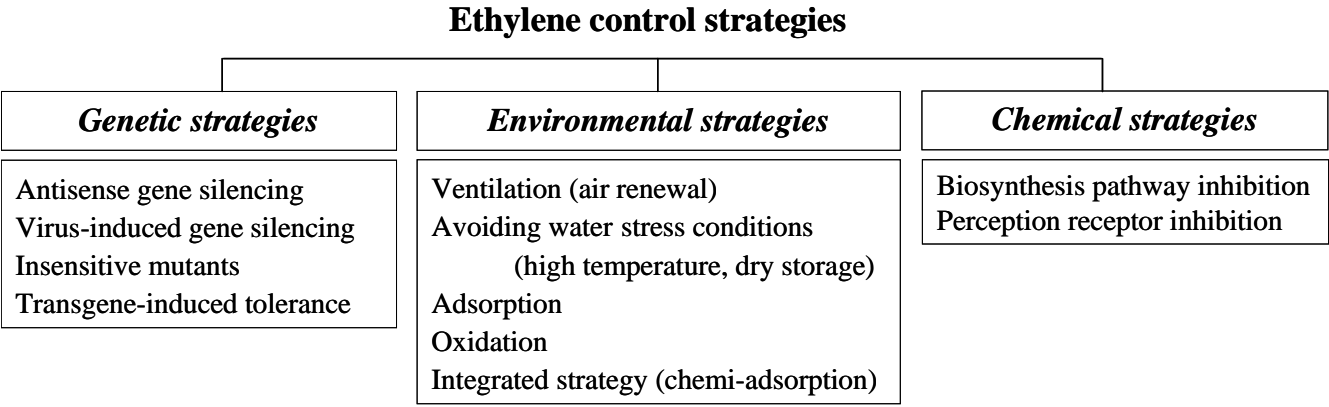


Figure 2 – Example of futuristic nanotechnology-based system for ethylene control in ethylene-sensitive cut flowers.

