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Postharvest management of insects in horticultural products by conventional and organic means, primarily for quarantine purposes

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Abstract

Purpose of review: The presence of arthropod pests in or on horticultural commodities has caused major disruptions in the storage, processing and shipment of these products. Management of these pests has posed a problem to humans for thousands of years. Current technology has led to the development of numerous means (chemical, mechanical or procedural) to control these pests. For the most part, postharvest pest control is focused on trade and exports. The accidental introduction of a pest into a place where it is not known to be present has resulted in the establishment of quarantine restrictions and export treatment requirements. This review focuses on the most current state of postharvest and quarantine treatments in development and currently in use on horticultural products. The current implementation and acceptance of these treatments is also addressed.

Findings: Conventional postharvest pest control measures include treatments with chemical fumigants and topical pesticides. Concerns over environmental pollution and human health have obstructed the use of conventional chemicals and fumigants and further development of new chemicals for postharvest treatments. Irradiation is considered a conventional treatment, however, it does not use chemicals nor does it result in detectible residues in the commodity. Improvements in engineering commercial irradiators such as restricting source exposure, and the development of more powerful X-ray converters of electron beams, as well as refinement of generic treatments for groups of pests, had led to the expansion of this treatment to achieve quarantine goals.

Directions for future research: Organic compliant postharvest treatments have received much attention and are the area of the most research. These treatments can include topical treatments with organic, natural pesticides and biologically derived fumigants, temperature extremes, modified atmospheres, and other novel physical treatments. The status of postharvest treatments for the control of arthropod pests both approved and in development is discussed.

Keywords: fumigation; controlled atmospheres; heat treatments; cold treatments; irradiation

Abbreviations

CA	Controlled Atmospheres
COS	Carbonyl Sulphide
EDB	Ethylene Dibromide
EF	Ethyl Formate
MeBr	Methyl Bromide
MI	Methyl Iodide
PPQ	Plant Protection and Quarantine
Q-PS	Quarantine and Pre-shipment
SF	Sulphuryl Fluoride

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Introduction

The presence or potential presence of arthropods on and in horticultural products shipped from areas where the pest is present to areas where is it not has been the source of many interstate, inter and intra country trade issues for many years. The use of chemical fumigants started in the 1920s and continued extensively up to the 1980s. In the late 1980s the fumigant ethylene dibromide (EDB) [1] was found to be linked to cancer, and in 1984 it was removed from the chemical register for use within the USA. Methyl Bromide (MeBr) became the fumigant of choice after the demise of EDB, and proved to be a reliable fumigant not just for fresh horticultural products, but for soil and structures as well. However, in the 1990s MeBr became the target of the Montreal Protocol after being found to be an ozone depleter [2]. Although the manufacture and use of MeBr would be stopped and then reduced for soil and structural uses under the Montreal Protocol, its use for quarantine and pre-shipment (Q-PS) was exempt. In recent years, however, there has been a major push for the development and implementation of alternative treatments to help in further reducing our reliance on MeBr.

Postharvest treatments can include conventional chemicals, irradiation and organic treatments. Chemical treatments such as fumigants, pesticide dips and detergents are considered conventional since they do not fit the organic standards of the USA and many other countries. Among the many chemical fumigants identified for controlling postharvest arthropods are phosphine [3**] and sulphuryl fluoride (SF) [4].

Perhaps the most successful and widely accepted non-chemical quarantine treatment is the use of ionising radiation [5**]. Although irradiation is considered a physical treatment, it is not commonly considered an 'organically compliant' measure, even though it does not render the commodity or affected arthropods radioactive nor does it leave any detectable residues deemed to be harmful to human or animal health [6*, 7*].

Many of the organic treatments developed rely upon the use of physical treatments such as the use of temperature extremes (eg, short term high and longer term low temperatures) as well as the use of controlled atmospheres (CAs) [8**, 9**]. High temperature treatments can include, but are not exclusive to, hot water dips, hot forced air, vapour heat, microwave and radio frequency. Low temperature treatments generally use long term cold storage above freezing, but there have been limited uses for freezing and flash freezing to control postharvest pests [10]. The application of CAs has also gained much interest, especially the use of CA in combination with temperature extremes [9**, 11*]. In addition to physical treatments, a number of chemicals that meet organic requirements have been investigated, such as neem [12*], vegetable oils [13**] and biofumigants [14].

There are numerous procedures and policies in place that address the potential of invasive pest establishment. These include the systems approach, pest free zones, areas of low pest prevalence, sterile insect releases and pest risk assessments [8**, 15**]. These techniques do not always include direct commodity treatments and are covered in previous reviews [8**]; therefore, will not be covered here.

This review addresses the most current state of postharvest and quarantine treatments in development and currently in use on horticultural products. The current implementation and acceptance of these treatments is also addressed.

Conventional treatments

According to the United States Department of Agriculture's (USDA) Animal and Plant Health Inspection Service (APHIS) Treatment Manual [16**], the only approved fumigants are MeBr, sulphuryl fluoride (SF) (Vikane) and phosphine. Phosphine can come in two forms, aluminium phosphide and magnesium phosphide. Fumigations with SF and phosphine are modifications of traditional MeBr fumigations. Most of the fumigations with SF and phosphine are for stored products, but there are some treatments for fresh fruits and vegetables.

Methyl bromide

MeBr is still the most popular and widely used fumigant in the USA for postharvest and quarantine uses. Treatments have been used to control insects, ticks and mites, nematodes, snails and slugs, as well as many plant diseases caused by fungi [3**]. MeBr uses in the USA for QP-S has to follow the Section 18 Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) Guidelines for Quarantine Exemption [17**]. Emergency uses of MeBr are granted if the fumigant is needed to control the introduction or spread of an invasive species. To continue MeBr fumigation for quarantine uses, the commodity group needs to file and receive approval for Critical Use Exemption, which, when granted, is valid for 3 years. Under these guidelines when MeBr is used for food or feed fumigation, the fumigator must monitor gas concentrations during the aeration period to determine when the levels of MeBr are low enough for safe removal of the commodity from the fumigation chamber or the tarp enclosure.

In the APHIS treatment manual [16**], there is a table (Figure 2-3-1) that lists about 20 commodities, ranging from avocadoes to edible podded legume vegetables that are covered by the FIFRA Section 18 [17**] exemption until March 3, 2010. The USDA-APHIS Treatment Manual [16**] also lists treatment schedules for MeBr fumigation of fruits, nuts and vegetables (T101). In T200 there are MeBr treatment schedules for propagated plant materials spread throughout the section, and in T300 there are schedules for miscellaneous plant products. Other MeBr fumigation schedules exist for containers and other commodities not directly related to food or feeds.

Sulphuryl fluoride

Sulphuryl fluoride has been used as a fumigant primarily against pests in wood and wood products [3**, 4]. However, it has also been tested for use against insects in chestnuts [18] and fruit flies [19] with varying results. Vinghes and Ducom [18] reported that SF was effective against young larvae of the chestnut fruit tortrix *Cydia splendana* (Hübner) or the chestnut weevil *Curculio elephas* (Gyllenhal). In this instance, egg tolerance to SF was not an issue since eggs were not present in the commodity at the time of harvest. Treatments of melon fly, *Bactrocera curcubitae,* and oriental fruit fly, *Bactrocera dorsalis*, [19] were less successful due to egg tolerance of the SF fumigation. Dow Chemical Company does have a registration for using SF in postharvest treatment of dry fruits, nuts and grains under the trade name *ProFume* (EPA Reg. No. 62719- 376-AA). Treatments with SF can last very long, up to 72 h, and are still not effective against eggs of insects, most likely due to low permeability of the chorion to this gas [20].

Phosphine

Phosphine is recognised as the 'go to' fumigant for structures, many stored products and some fresh foods [3**, 21*]. Aluminium phosphide, magnesium phosphide, ECO$_2$FUME® and VAPORPH$_3$OS® are phosphine formulations that are currently approved for use by the Plant Protection and Quarantine (PPQ) Program [16]. ECO$_2$FUME® is a compressed gas mixture of phosphine and CO_2. This combination is more effective against insects since it combines the respiratory stimulant of CO_2 with the toxicity of phosphine. VAPORPH$_3$OS® is a pure form of phosphine in a high-pressurised tank, with the advantage that the release of the fumigant is instantaneous and does not rely upon chemical reaction with metals. Phosphine is highly reactive with metals and poses a problem in structural fumigations where equipment and computers cannot be removed. Approved APHIS treatments using phosphine fumigation include: cotton and cotton products against boll weevil *Anthonomus grandis* (T301-d-1-2); rice against panicle rice mite, *Steneotarsonemus spinki* (T303-a-1); tobacco as a pre-shipment requirement against unspecified stored products pests (T308-b-1); and hay against *Mayetiola destructor* (Hessian fly) and *Oulema melanopus,* (cereal leaf beetle) (T311) [16]. Phosphine treatments are being developed for asparagus, lettuce, broccoli and strawberry against Western flower thrips, *Frankliniella occidentalis* [22]. There have also been studies on the effects of phosphine on cut flowers [23] and on chrysanthemum cuttings (cv. Pollyanne) against *Spodoptera littoralis*, with limited success against the larvae, but not at the 1–2 days old egg stage [24]. Wolfenbarger [25] reported complete control of the Mexican fruit fly in grapefruit using a phosphine fumigation of 0.5 g/m^3 at 26.3 ± 3°C for 4 days. The drawback to this treatment is that the duration of the treatment at such a high temperature caused approximately 22% fruit damage.

Carbonyl sulphide

Carbonyl sulphide (COS) is another potential MeBr replacement fumigant and has been used for fumigation of stored products and structures [20, 26]. It has been used to fumigate structures where insect resistance to phosphine has been developed [3**]. Tests with COS at 80 mg/L on nectarines resulted in 87% codling moth (*Cydia pomonella*) mortality, but the fumigant dosage was insufficient to reach the desired probit 9 level (99.9968%) [27]. COS fumigation of lemons against medfly was marginally successful at 70 mg/L for more than 8 h [28]. The two major drawbacks to this treatment are the duration and off flavours in the lemons following treatment. Fumigations of dried fruits and nuts are more promising. Zettler *et al.* [29] demonstrated that five species of stored product insects: larval navel orangeworm, *Amyelois transitella* (Walker); adult sawtooth grain beetle, *Oryzaephilus surinamensis* (L.); adult driedfruit beetle, *Carpophilus hemipterus* (L.); adult cigarette beetle, *Lasioderma serricorne* (F.); and adult confused flour beetle, *Tribolium confusum* Jacquelin duVal were controlled using 24 h fumigation of COS with a concentrations × time (CT) of 1,008 mg/L/h. While COS fumigation appears to be feasible for stored products, treatments for tropical fruits and flowers are more problematic. Treatments of 'Apple' banana (*Musa* sp.), avocado (*Persea americana* Mill.), mango (*Mangifera indica* L.), papaya (*Carica papaya* L.) and red ginger (*Alpinia purpurata* (Vieill.) K. Schum indicated that ginger was the most sensitive to the treatment, but that avocado and papaya may tolerate COS fumigation to control surface pests [30].

Propylene oxide

Propylene oxide has been tested as an alternative fumigant for many stored products [31]. Propylene oxide fumigation was used for 4 h to control *Plodia interpunctella* (Hübner) in peanuts, almonds and walnuts at doses of 60.3, 72.1 and 93.1 mg/L, respectively, and resulted in 99% mortality with acceptable residue levels in the nuts [31]. Combining propylene oxide fumigation with low pressure or elevated CO_2 improved the control of *Tribolium castaneum* [32]. Other studies on the effectiveness of propylene oxide fumigation at low pressures against four stored products insects, *T. castaneum* (Herbst), *P. interpunctella* (Hübner), *Ephestia cautella* (Wlk.) and *O. surinamensis* (L.), achieved 99% mortality of all life stages of the tested species at a CT of 104.4 mg/L/h [33].

Methyl iodide

Methyl iodide (MI) was identified early on as a potential replacement to MeBr after MeBr was identified as an ozone depleter [3**, 34]. MI became a candidate because of its low phytoxicity to fresh fruits and vegetables [35]. It was found that MI was generally more effective than MeBr against postharvest pests. Russian wheat aphid, *Diuraphis noxia* (Mordvilko), Vine mealybug, *Planococcus* ficus (Signoret), Red scale, *Aonidiella aurantii* (Maskell), Grain moths, *Sitotroga cerealella* (Olivier) and two-spotted spider mites, *Tetranychus urticae* (Koch), were controlled by MI similarly or better than MeBr at the same concentrations [35]. In the same study it was reported that MI treatment of beans, sugar beets, wheat, sweet orange and rough lemon resulted in minimal damage. In another study, treatment of lemons against

California red scale (*A. aurantii*) and nectarines against codling moth (*C. pomonella*), showed promise [27]. Nectarines treated with 25 mg/L of MI resulted in minimal phytotoxicity and 100% control of codling moth, while lemons treated with a concentration ≥ 40 mg/L, needed to control red scale, resulted in extensive fruit damage. This damage was alleviated by conditioning the lemons at 15°C for 3 days.

Hydrogen cyanide and cyanogen

Hydrogen cyanide, a well known poison [3**], was used for many years as a rodenticide and insecticide in stored grains. It was also used to fumigate fresh fruits [36]. Its continued use is greatly restricted due to its high toxicity to humans. There are no schedules for hydrogen cyanide fumigation in the USDA-APHIS Treatment Manual [16]. Cyanogen, a gas produced from the reaction of cupric sulphate with potassium cyanide, has been investigated as a fumigant for grains in Australia [37]. Tests against five species of stored products pests, *Rhyzopertha dominica* (F), *Sitophilus granarius* (L), *Sitophilus Oryzae* (L), *T. castaneum* (Herbst), *T. confusum* Jacquelin du Val and *E. cautella* (Walker) demonstrated that exposure to cyanogen at 1.3 mg/L for 24 h controlled all external stages, while a 5 day exposure at 13.7 mg/L was needed to control internal stages of these pests [37].

Ethyl formate

Ethyl formate (EF) is a potentially useful, albeit dangerous fumigant [3**]. Most of its uses have been against stored products insects [34, 38**–40] while only a few studies have been performed on fresh commodities. One study on table grapes demonstrated the effectiveness of EF on Western flower thrips, *F. occidentalis* (Pergande), grape mealybug, *Pseudococcus maritimus* (Ehrhorn) and Pacific spider mite, *Tetranychus pacifiais* McGregor, within the tolerance range of grapes [41]. The major exceptions were omnivorous leafroller pupae, *Platynota stultana* Walsingham. EF fumigation of onion thrips, *Thrips tabaci*, at 27 g/m^3 for 2 h was effective against all but the egg stage [42]. EF fumigation of fresh strawberries against Western flower thrips and two-spotted spider mite were not considered entirely successful as it required multiple fumigations to control the pests, resulting in loss of market quality [43].

Sulphur dioxide

Sulphur dioxide has been shown to be very effective as a fumigant for stored products and structures [3**]. It is also commonly used as a fungicide for litchi [44] and longan [45], and as a preservative for dried apricots [46]. Sulphur dioxide low temperature, slow release treatments pads were used with variable efficacy against western flower thrips, *F. occidentalis* Pergande; grape mealybug, *P. maritimus* (Ehrhorn); Pacific spider mite, *T. pacificus* McGregor, two-spotted spider mite, *T. urticae* Koch; and omnivorous leafroller, *P. stultana* Walshingham [47]. There was complete control of western flower thrips, two-spotted spider mite and omnivorous leafroller, while there was <8% survival of grape mealybug and <1% survival of Pacific spider mite.

Pesticides

There are a few pesticides being used to treat horticultural commodities for disinfestations. These include alkanes [48, 49], borate [50, 51], chlorpyrifos [52], imidacloprid [51] and sodium hypochlorite [53]. Most of these, except for the alkanes, are for nursery stock, scion wood, or wood and wood products. Two studies conducted in Australia assessed the use of alkanes, petroleum spray oils normally used in orchards, as postharvest dips to control light brown apple moth, *Epiphyas postvittana* Walker, on citrus [49], and mites and mealybugs on citrus [48]. Application of (Ampol Citrus Postharvest Dip, a formulated C15 alkane) at 30 mL/L on oranges resulted in 99% mortality of 3rd instars of Light brown apple moth in the calyx end [49]. Postharvest dips of oranges with CDP were also shown to be effective against mites and mealybugs [48]. The major problem with pesticide treatments of fresh fruits and vegetables is the restrictions on residues and the ‘no-tolerance’ stance of many countries when it comes to residues on fresh commodities.

Irradiation

Most of the original research on the effects of radiation on insects was focused on the development of the sterile insect technique [54]. However, when commercial irradiators became more abundant and efficient, a more concentrated effort was made to develop quarantine treatments for horticultural products [3**]. Although radiation treatments of horticultural products do not render the commodity radioactive, organic producers, regulators and some consumers are reluctant to accept this treatment. At the doses recommended by the USA Food and Drug Administration for fresh foods, which are below 1,000 Gy (1 kGy) [55], the production of free radicals are well within the range for normally processed foods (ie, cooked foods). Nevertheless, irradiation has received a less than favourable reputation among those supporting ‘pure foods’.

Irradiation is usually performed on a commercial scale on packaged product. It is not easily applied in warehouses or other remote locations. Irradiation is most typically applied using a source irradiator, such as cobalt Co^{60} or caesium Cs^{137}, or electronic source such as an electron beam or x-ray conversion of an electron beam. All sources produce gamma radiation, which is also called ionising radiation. In the USA Cs^{137} is not preferred since a leak of this material poses a threat to ground water. Therefore, most irradiators in the USA are either Co^{60} or x-ray. The origin of the radiation has no effect on the efficiency of the treatment. It is only the absorbed dose that is the ‘active ingredient.’

As a quarantine treatment, irradiation is easy to apply, quick, and generally safe. Considerable research has demonstrated that irradiated insects are unable to either continue development or successfully reproduce. The fact that most irradiated insects do not directly die as a result of radiation treatment was an initial concern for regulatory agencies. In addition, there was a general lack of consistent biochemical markers that could be used to indicate whether an insect had received an appropriate dose of radiation to render it biologically inactive. With continued research and improved dosimetry and documentation, regulatory agencies became more comfortable with the ‘wriggler’ issue.

In a recent review, Follett [5**] listed USDA-APHIS [16**] approved generic irradiation treatments for 22 quarantine pests. Most of these treatments are against tephritid fruit flies, for which there has been considerable research on the appropriate doses of radiation needed to either prevent development or render the flies sterile. There are also treatments against a few Lepidoptera, Coleoptera and two species of scale [55**]. With the USDA-APHIS leading the way, international regulatory and plant protections bodies, like the IAEA (International Atomic Energy Agency) [56, 57] and the IPPC (International Plant Protection Convention) [58] have issued guidelines for irradiation of foods to meet export and quarantine restrictions.

Stored products

The major problem with irradiation of stored products is the sheer volume of product that needs to be treated. Considerable research has proven that although irradiation against many stored products pests is effective, volume and cost have proven to be inhibitory to its application [59, 60]. Treatments have been developed to control stored product pests grains, dried fruits and nuts. The major pests in grains for which irradiation treatments have been developed are Angoumois grain moth, *S. cerealella* (Olivier) and Indianmeal moth [61], where a generic dose of 600 Gy has been recommended for all insects in grains, mostly due to the high radiotolerance of the Angoumois grain moth. Most of the irradiation treatments against pests in dried fruits and nuts has focused on the Indianmeal moth [62] where it was found that a dose of 350 Gy was required to prevent egg hatch and adult development from irradiated larvae.

Fresh fruits

Early on in the investigations into viable alternative quarantine treatments to replace MeBr, irradiation was identified as the best alternative [63]. The most successful application of irradiation as a quarantine treatment has been with tropical fruits originating in the Hawaiian islands headed to the USA mainland [5**, 8**]. Considerable effort was made by the USDA-APHIS to set in place protocols involving the treatment of tropical fruits to meet quarantine requirements against tephritid fruit flies [5**, 16**]. Additional research on refining doses to sterilise tropical fruit flies reduced the required dose, making it possible for more types of fruits to be treated while maintaining market quality [5**, 8**]. In addition, the development of generic doses for groups of insects, like fruit flies, Lepidoptera, mites and scale insects will facilitate the international acceptance of this treatment [5**].

Fresh vegetables

Sweet potatoes are the only vegetable that has approved treatments against Sweetpotato weevil, *Cylas formicarius elegantulus* (Summers), West Indian sweetpotato weevil, *Euscepes postfasciatus* (Fairemaire), and Sweetpotato vine borer, *Omphisa anastomosalis* (Gueneˊe) [5**].

Organic treatments

Most organic quarantine treatments tend toward the physical treatment category. However, there are an increasing number of organically compliant chemicals that are being investigated and used to meet quarantine restrictions.

Chemicals

Many of the chemicals that meet organic standards which have been tested have been used as fumigants. These include aldehydes [64], biofumigants [14, 65], ethanol vapour [66], ozone [67], p-cymene [68], essential oils [69] and botanical essential oils [70]. Topical organic pesticides include botanicals [71], limonene [72], linalool [73], pyrethroid [74], and spinosad [75].

Fumigation with the aldehydes propanal, (E)-2-pentenal or 2-methyl-(E)-2-butenal [64] showed great potential for control under vacuum fumigations against aphids, and may also be useful against mealybugs, thrips and whitefly. The volatile compounds from the fungus *Muscodor albus* was shown to be effective against codling moth in apples [14] and potato tuber moth in potatoes [65]. Ethanol vapours in combination with cold storage did control light brown apple moth in apples, however there were discernable levels in the fruit up to 4 weeks following treatment [66]. Ozone has long been investigated as a potential organic fumigant, but since it is not penetrating, due to its inability to cross high humidity or water barriers, it is only effective for surface pests. Hollingsworth and Armstrong [67] found that ozone was effective in controlling mealybugs and thrips on ornamentals. The essential oil component p-cymene [68] was shown to be effective against Western flower thrips when combined with elevated CO_2. Essential oils from of *Caesulia axillaris* and *Mentha arvensis* were effective in protecting stored grains from *S. oryzae* and *T. castaneum*, at 1,300 and 600 ppm, respectively [69]. The essential oil of *Cymbopogon martini* was used as a botanical fumigant to protect stored grains and legumes from beetles *Callosobruchus chinensis* and *T. castaneum* [70].

Eight potential botanical pesticides were tested against nursery white grubs of *Popillia japonica* Newman, *Rhizotrogus majalis* (Razoumowsky), *Anomala orientalis* Waterhouse, and *Cyclocephala borealis* Arrow [71]. It was found that Armorex, a formulation containing extracts from diverse botanical sources, including 84.5% sesame oil, 2.0% garlic oil, 2.0% clove oil, 1.0% rosemary oil and 0.5% white pepper extracts, were very effective in protecting nursery stock. A 1% solution of limonene in combination with surfactants was shown to control white flies and mealybugs on ornamentals

[72]. Phytotoxicity was noticed on some ferns, ginger and delicate flowers, but it was tolerated by plants with thick, waxy leaves. The botanical linalool was used to protect stored grains from *Zabrotes subfasciatus* (Bohem.) where 48 h exposures resulted in 100% mortality of males, but only 50% mortality of females [73]. Pyrethroids have been used as contact insecticides in the field for many years. However, Hollingsworth [74] used pyrethroid sprays to prevent infestation of western jacket queens in Christmas trees harvested in Oregon and exported to Hawaii. This treatment, in combination with mechanical shaking, was shown to be effective in preventing the accidental entry of this pest into Hawaii. The contact bioinsecticide spinosad, derived from the fermentation of the soil micro-organism *Saccharopolyspora spinosa*, was shown to be effective at a dose of 50 mg TS/kg to control the cigarette beetle, *L. serricorne* (F) and the tobacco moth, *Ephestia elutella* (Hübner) in stored tobacco [75].

Cold

Low temperature treatments are perhaps the most common and widely used postharvest disinfestation procedures in practice. Many tropical pests cannot withstand extended exposures to above freezing, low temperatures. The most common cold treatments exist for fruit flies infesting citrus [76–80]. Cold treatments also exist for fruit flies in carambola [81], blueberries [82] and apples [83]. Cold storage has also been shown to be effective against some Lepidopterous pests such as oriental fruit moth in apple [84], Indianmeal moth and navel orange worm in nuts [85]. Cold storage was also shown to be effective against the mealybug, *Pseudococcus affinis*, in apples [86].

The USDA-APHIS-PPQ Treatment Manual lists 10 cold treatment schedules [16**]. Most of the schedules are to control fruit flies. The exceptions are T107-e and -k, which are against false codling moth and Natal fly, T107-g which is against pecan weevil, and T107-f, which is for Ya pears from China with no pests specified.

The most important aspect of successful cold treatments is that the pulp temperatures remain at the specified temperature for the specified duration. Too many times, air temperature is specified and monitored without regard to the commodity or the effects on the infesting pest. The most successful cold treatments are those that require freezing. Freezing is a common practice in the Pacific Northwest for caneberries [87, 88]. Freezing is predominately for preservation, and not quarantine purposes. However, it does prevent the spread of co-harvested orange Tortrix larvae and other pests. Freezing has also proven to be effective for garbanzo beans against cowpea weevil, *Callosobruchus maculates* [10]. Freezing at -15°C for at least 48 h has also been reported to be effective in the control of Indianmeal moth in dried fruits and nuts where diapausing larvae are potentially present [85]. The USDA-APHIS Treatment Manual [16**] lists two freeze schedules, T110-a for quick freeze and release of product and T110-b for freeze and destruction.

Hot water

Hot water dips are perhaps the oldest and most widely used heat treatments for fresh fruits and vegetables [89**]. Most of the commodities treated with hot water dips are tropical and sub-tropical fruits and vegetables. These include oranges [90, 91], mangoes [92–94], guavas [95], longan [96, 97], lychee [96, 97], grapefruit [98], limes [99], bananas [100], some fresh cut flowers [101, 102], and even apples [103]. The advantage of hot water dips is the speed at which the target pulp temperatures are attained and the short duration of the treatment. However, there have been problems with phytoxicity and maintenance of pulp temperatures that make hot water dips problematic. The USDA-APHIS Treatment Manual [16**] lists 10 hot water dips on fresh fruits and plant materials against arthropod pests. There are also a number of hot water treatments on plant materials to control plant diseases and nematodes. One treatment, T201-p-3 is a catch-all treatment for plant materials that cannot withstand fumigation.

Hot air

Hot air treatments can also be called hot-forced air or vapour heat treatments. Microwave and radio frequency are also forms of hot air treatments [8**, 104]. These treatments were developed for commodities that could not withstand hot water dips or for which hot water dips were not feasible, as in the case for logs and lumber, and dried fruits and nuts. Hot air treatments were first developed for tropical fruits such as papaya [105–107], mangoes [108–110] and citrus [111–114] against, predominantly, tropical fruit flies. Hot air treatments have also been developed for numerous other fresh fruits [115, 116], vegetables [117, 118], plant materials [67, 119] and lumber [120–122]. There are six hot-forced air and vapour heat treatments in the USDA-APHIS Treatment Manual [16**] for disinfesting citrus, mango, papaya and rambutan. In the ISPM15, there are requirements for heat treatments for wood and wood products to prevent the spread of wood boring pests [58].

Microwave and radio frequency are more rapid methods of heating horticultural commodities [123**–125]. Microwave has been successful for treating logs [126, 127], rice [128], and stored products [129]. Radio frequency treatments have been very successful in treating dried fruits and nuts [130–133]. The advantage of microwave and radio frequency treatments is that they can be performed on a large scale and in flow-through systems, and treatment times can be very short, normally in the span of a few minutes.

Controlled atmospheres

Normally, CA treatments are combination treatments, with temperature being another variable in the treatment. CA or modified atmosphere (MA) means the alteration of the levels of atmospheric gases beyond those levels found at standard temperature and pressure [9**]. Most CA treatments are conducted at low temperatures because the low oxygen, elevated carbon dioxide levels slow fruit metabolism and allow for longer cold storage without increasing chilling damage [132**]. For the most part, low temperature CA is effective against arthropods because it allows the commodity to be stored at low temperatures for a prolonged period, and the arthropod incurs chilling mortality. The low temperature suppresses insect respiration, and the CA does not have as much of an effect on insect mortality [125*]. However, ultra low O_2 treatments or very high CO_2 treatments at low temperature have been shown to be more effective at low temperatures [9**]. Although numerous low temperature CA treatments have been developed, none exist in the USDA-APHIS Treatment Manual.

The combination of CA with elevated temperatures has been shown to be very effective for fresh fruits [9**, 133–144]. The reason combination high temperature-CA treatments work so well is that the low O_2, high CO_2 environment prevents insects from acclimating to the heat load, causing them to die about 2 times faster than under heat alone [145]. There are five high temperature CA (also called CATTS for Controlled Atmosphere Temperature Treatment System) treatments for apples, sweet cherries, peaches and nectarines in the USDA-APHIS Treatment Manual [16**]. These are the first CA treatments to be entered into the manual. Additional research indicates that the duration of the high temperature CA treatment can be shortened if it is followed by cold storage [146]. Presumably, the heat treatment under CA compromises insect tolerance to prolonged, approximately 30 days, of cold storage.

Low pressure treatments can also be considered modified atmosphere treatments. These hypobaric treatments operate under vacuum and reduce the pressure below atmospheric pressure, 760 mmHg (torr), and in turn, reduce the oxygen level [9**]. Hypobaric treatments can be accomplished by placing the commodity in a specialised container where pressure can be reduced [147] or in a sealed bag where a vacuum can be applied [148, 149].

Novel treatments

There are a number of treatments that are being developed that do not fall into any generalised category. These include high pressure washing and surface vacuum to remove surface pests [150–154], high hydrostatic pressures [155], metabolic stress disinfection and disinfestation (MSDD) [156], plasma discharge [157], and pulsed electronic fields [158]. None of these treatments have been approved for exports.

Conclusions

The presence or potential presence of pests in horticultural products has been the focus of many procedures and treatments to prevent continued damage to the products or accidental movement of pests from one area to another. Treatments that have been developed are generally tailor-made to fit within commodity tolerances and pest intolerance. Conventional treatments rely on the use of chemicals. Many of these chemicals, by their nature, are harmful to either the environment or human health. Alternative treatments are being developed to be more environmentally friendly and have less impact on human health. Many of these treatments have already bridged the gap between research and implementation, such as the case for irradiation treatments. Many other treatments are still in development and may require more research to gain widespread acceptance.

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