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History and use of heat in pest control: a review

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This review describes the history and use of heat in the management of a wide range of agricultural and structural pests. Definitions and concepts used in heat treatments are discussed as well as possible mechanisms of thermal lethality. Factors used in determining treatments are availability, costs, complexity, and other constraints. Heat can be used separately in multiple forms or in combination: fire, water-based and atmospheric, steam, vapor heat, dry heat, forced hot air, high temperature controlled atmospheres, electric fields, and electromagnetic energies. The early research into each of these strategies is presented, including design, temperature ranges, and target pests. An understanding of the development of thermal treatments will increase efficacy of pest control and adaptability, and will reduce duplication.

Keywords: control atmospheres; electromagnetic energy; postharvest; high temperature; treatments; soil; thermal energy

1. Introduction

Heat has had a variety of uses in human history, such as in cooking and in food preservation, but it was not used as a pest control method for stored products until the modern era. Heat can be generated by various methods: chemical oxidation and combustion, electrical resistance, and electromagnetic exposure. The manner in which heat is produced affects both the products and their pests.

1.1. Definitions and concepts

Postharvest treatments are a recent development. For most of human history, insect pests in stored products have been tolerated. However, two events led to the development of postharvest methods to eliminate insects. The first relates to the distribution of pest insects. Historically, the distribution of insects was limited by their biology and geophysical forces, but with increased travel by humans, particularly wide-ranging exploration and commerce, insects could be transported into new areas. If the insect had potential to inflict damage, even though it is a minor pest in its native range, measures that prevent its introduction and establishment would be highly beneficial. This observation has introduced a series of procedures and regulations pertaining to *quarantine* insects.

The second event involved the rapid development of agricultural technology, whereby surplus commodities could be stored until future consumption or transportation to distant markets for greater economic gain. To prevent damage by various insects during storage, particularly by beetles and moths, procedures were developed to reduce and control the populations of these pests, a process known as *phytosanitation*. Such an action may include inspection, testing, surveillance or treatment to prevent the introduction or spread of quarantine pests, or to limit the economic impact of regulated non-quarantine pests (IPPC 2007). *Quarantine* is a legal term, referring to exclusion of a product due to possible pests unless specific actions are performed. A *quarantine pest* has potential economic importance to the area endangered by it; the pest may not yet be present there, or may be present but not widely distributed and being officially controlled (IPPC 2007). Because of the complexities of modern commerce, the distinction between *quarantine* and *phytosanitation* is often unclear.

1.2. Overview and importance

1.2.1. Requirements

The term *heat* covers a variety of applications which can range from simple, such as an open flame or solar energy, to complex, such as the energyfrom a nuclear facility or a radio frequency unit. An energy source is the first requirement for heat treatments. Because heat is always associated with human societies, it is

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available, at least in its simplest form. Thus, heating differs from other physical methods, such as cooling, which is a biological and chemical strategy where agents must be introduced into apparatus. Furthermore, reducing treatment time is usually done at the expense of increased complexity, which increases costs; for example, a hot water dip takes longer, but is simpler than using radio frequency radiation. Sophisticated equipment may have requirements not readily available, such as electrical voltage or electromagnetic generators. Temperature monitoring devices also make heat treatments more complex.

1.2.2. Situations and purposes

Thermal treatments must be precise because of the narrow margin between efficacy and commodity tolerance to the temperature, particularly in fresh fruits and vegetables. Heat treatments have been accepted for commodities entering the USA and for interstate shipments (USDA 2005). Reviews of heat treatments can be found in Stout and Roth (1983), Armstrong (1994), Sharp and Hallman (1994), Mangan and Hallman (1998), Vincent et al. (2003), Yahia (2006), Beckett et al. (2007), Hansen and Johnson (2007) and USDA (2008).

1.2.3. Biological responses

Little is known about what causes thermal death. Most literature on the lethality of heat, such as that cited in this review, are descriptive, often providing elaborate mathematical models relating duration of temperature exposures to mortality in the target population. The mechanisms of thermal death are believed to involve denaturation or coagulation of proteins (Larsen 1943; Rosenberg et al. 1971; Kampina 2006) or damage to the cell wall (Bowler 1987). Toxic products may accumulate because of a metabolic disturbance (Fraenkel and Herford 1940; Cloudsley-Thompson 1962). The exact process varies with the conditions and does not apply to all situations. The thermal death point may be affected by humidity (Mellanby 1932), degree of starvation (Mellanby 1934), temperature acclimation (Mellanby 1954), or age (Bowler 1967; Boina and Subramanyam 2004). Other physiological effects of overheating (or hyperthermia) include increased metabolic rate, which also increases respiration and a rapid depletion of food reserves. If there is insufficient available atmospheric oxygen, then the pest essentially asphyxiates (Hansen and Sharp 2000). This is particularly true for aquatic insects where heated water loses dissolved oxygen, even though the outer temperature itself is not directly lethal.

Heat can adversely affect invertebrates by several different ways. Temperature exposure can be so severe as to cause immediate death (or *acute mortality*). This is essential for situations where pest elimination needs to be demonstrated before commercial transaction or movement across political boundaries, such as with meeting quarantine regulations (Hansen et al. 2000a, 2000b). If the intent is the eventual reduction of the pest where time is not an important factor, such as with soil sterilization (Nelson 1996a) or sanitizing fruit bins to reduce reintroduction by tree fruit pests (Hansen et al. 2006), then the long-term lethal effect (or *chronic mortality*) is desired.

Similarly, heat can cause sterility, so that future recruitment is prevented although the ''parent stock'' may still expend energy and time in reproduction (Isely 1938; Proverbs and Newton 1962; Okasha et al. 1970). Heat may affect behavior so that the targeted pest becomes susceptible to pathogens and natural enemies, such as predators and parasites. When some insects are exposed to sublethal high temperatures, they cease activity by going into a heat stupor (El Rayah 1970; Klok and Chown 2001; Slabber and Chown 2005), which would make them susceptible to predation and other causes of mortality. Heat could encourage the pest to move to another location and out of the treatment area, which may be useful when managing structural pests.

1.2.4. Strategies

Thermal pest control can be broadly divided into preharvest (or external) and postharvest (normally internal) strategies. Preharvest control includes applying heat treatments where the pest naturally occurs outside, such as with injurious insects in soil and structures. In these cases, heat is directed at where the pest resides. Besides acute pest mortality, these treatments can also incorporate long-term pest management components for population reduction, including sterility (Proverbs 1969) or increased susceptibility of the survivors to injurious agents (Ebeling 1990). Field-burning and soil-steaming are examples.

Postharvest control involves transporting the pest into a designated area, often as an infestation in a horticultural commodity, and treated under managed conditions within a specific structure, such as vapor heat for tropical fruits or soil sterilization in ovens. This strategy is more difficult because of the increased number of components used, including transportation and storage, and construction, operation and maintenance of specific treatment units.

1.3. Limitations

1.3.1. Commodity or substrate damage

Care for commodity quality must be considered when developing heat treatments for horticultural and agronomic commodities. When heat is used in pest control, the pest must be more sensitive to the treatment than the commodity (Tang et al. 2000; Wang and Tang 2001). Specific injury caused by heat to the treated commodity may include dehydration, loss of cellular membrane integrity, cellular leakage, disruption of protein and nucleic acid synthesis, inhibition of pigment synthesis, formation of surface burns, increased transpiration, and advanced senescence (Kays and Paull 2004). Because of the temperature stress on the commodity, the benefits of pest control must warrant the potential costs from thermal damage.

A similar relationship occurs for control of soil pests. Instead of a single commodity being affected, an entire ecosystem is affected during heat treatments (DeBano et al. 1998). The target pest may be eliminated, but also beneficial organisms, such as mutualists (e.g. mycorrhizae), may be removed. Soil may need to be reinoculated to restore its vigor. Compaction, dehydration, and changes in soil structure and chemistry also need to be considered.

Diverse sorts of problems accompany thermal control of structural pests (Nicholson and von Rotberg 1996). Besides surface blemishes, such as burning and paint discoloration, heat may damage plastics and electrical components. If these materials cannot be removed during treatment, they need to be protected.

1.3.2. Complexity

Heat treatments can range in complexity from burning vegetation in a field to complex processes directed by sophisticated computers and thermosensers. Solar heating can consist of direct exposure to the sun or under a cover. Hot water dips and steam generally involve just heating water with thermomonitoring. Forced hot air and vapor heat, including controlled atmospheres, require specialized compartments for heating and moving air, and employ microprocessors and computers to regulate temperature, atmospheric composition, humidity, and air motion. Electromagnetic treatments are the most complex because they involve producing energy at specific frequencies, a compartment to contain micro/radiowaves and other safety equipment, fiber optic temperature sensors, and a microprocessor to regulate radiation exposures. Some treatments also require a special building to house the apparatus.

1.3.3. Cost

A major factor in implementing heat treatments is cost. Unless the benefit exceeds the investment required for using heat, the treatment will not be employed, regardless of how effective it is. Small-scale tests, such as those done in the laboratory, may appear promising, but constraints increase when they are expanded for commercial use, such as in time, cost, and complexity of equipment. Furthermore, heat may age or damage the product so that long-term storage is a problem, which reduces the market value of the commodity.

2. Survey of heat treatments

2.1. Approaches

The use of heat to control pests developed from the simple use of fire for soil to highly technical methods of using electromagnetic energy (Table 1, Figure 1). The development of thermal control strategies would lead into areas not originally intended – for example, expanding the use of steam from a soil treatment to include dry goods. A specific heat treatment can be derived from different methods, such as dry heat originating from combustion or from electrical heaters. Electricity can be used to generate hot water and steam, direct dielelctric and ohmic heating, indirect resistance heating, or electrocution. Solar heating can be a source for dry heating or in a separate grouping. Furthermore, different thermal methods can be used, separately or in combination, for the same commodity, such as hot water and radio frequency. Dry heat is used to treat both structures that contain a commodity and the commodity itself, such as granaries and mills along with grain that may contain stored product pests. Because of this considerable overlap, thermal treatments do not fit into tight, neat categories.

Table 1. Comparison of heat treatment strategies.

Strategy	First used	Commodity	Advantages	Disadvantages
Hot water	1925	Fruits, bulbs, ornamentals, seeds	Simplest, efficient	Surface heating first, fuel costs
Vapor heat	1913	Fruits, vegetables	Relatively simple	Expensive facilities, surface heating first, slow
Forced hot air	1989	Fruits, vegetables	Product quality retained	Expensive facilities, surface heating first, slow
Dry heat	1792	Structures, grains, fibers, museum artifacts, books	Simple, versatile known technology	Surface heating first, slow
CATT	1996	Experimental	Faster than other air methods	Surface heating first, complicated, expensive facilities
Solar	2001	Experimental, structures	Simple, inexpensive	Variable effects
Elecromagnetic energy	1927	Experimental, grains, seeds, nuts	Very fast, internal heating first	Expensive facilities, Variable effects

CATT = Controlled atmosphere temperature treatment.

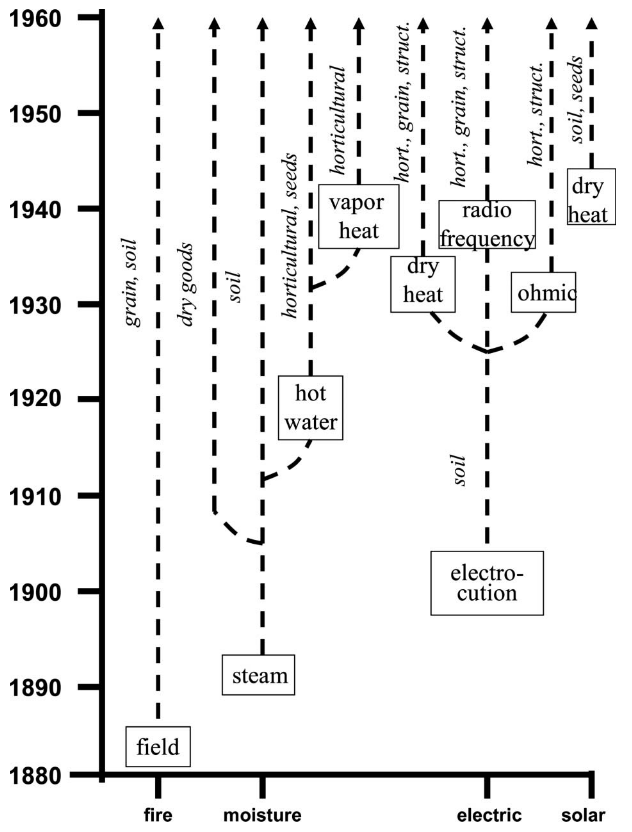

Figure 1. Flow diagram showing the developmental relationships among thermal treatments.

2.2. *Fire*

Soil contains microbes, seeds or weeds, nematodes, insects and other arthropods, many of which are deleterious to plants. All of these are susceptible to thermal death. Burning of vegetation was proposed for controlling soil pests of field and pasture crops (Loew 1909; Kelly and McGeorge 1913; Milbrath 1930). Burning in the greenhouse to remove soil pests is problematic and damages structures.

2.3. *Water-based and atmospheric*

2.3.1. *Hot water*

Hot (>40°C) water baths and dips are the simplest of the heat treatments. They are anaerobic and have high energy transfer because of the aqueous medium. One of the earliest attempts at postharvest treatment of a horticultural commodity was in 1909 by immersion in hot water to control tarsonemid mites (Cohen 1967). Later, a hot water treatment (43.5°C) for 3 h was used against the stem nematode, *Ditylenchus dipsaci* (Kühn) Filipjev (Tylenchidae: Anguinidae), a pest of narcissus bulbs (Ramsbottom 1925; Doucette 1926). Fleming and Baker (1928) described using hot water at 44.4°C to control all life stages of the Japanese Beetle, *Popillia japonica* Newman (Coleoptera: Scrabaeidae), in soil. Newhall (1930) reported that hot water treatments (60–71°C) of soil were unsuccessful in controlling root-knot nematodes. Hoshino and Godfrey (1933) determined the thermal death points of the eggs and larvae of the root-gall nematode, *Heterodera radicicola* (Greeff) Mull. (Tylenchida: Heteroderidae), from hot water dips over a range of temperature. Staniland and Barber (1937) described an apparatus for hot water treatments and shortened the treatments to 17 min for nematodes within bulbs and 78 min for ‘‘eelworm wool’’ outside of the bulbs. These hot water treatments were expanded to include the narcissus bulb fly, *Merodon equestris* (F.) (Diptera: Syrphidae), and the lesser bulb fly, *Eumerus tuberculatus* Rondani (Diptera: Syrphidae) (Weigel 1927). Gadd (1950) demonstrated that a hot water treatment, 10 min at 45–47°C, controlled fungal infections of pea seeds. Later, Goheen and McGrew (1954) killed endoparasitic nematodes in strawberry roots by using a hot water bath for 2 min at 53°C. For fiber pests, Clark (1928) reported that hot water (60°C) immersion for 5 s kills dermestid larvae and eggs, and that heat at 49°C for 11 min kills all life-stages of tineid clothes moths and some dermestid species, with the egg stage being the most heat resistant. Goheen and McGrew (1954) found that a hot water treatment of 2 min at 53°C was sufficient to control endoparasitic nematodes in roots of dormant strawberry plants. Miller and Stoddard (1956) expanded this treatment to 4 min to control the fungus, *Rhizoctonia solani* Kühn. Staniland and Woodville (1967) discussed the specifications for constructing hot water facilities.

Although the hot water procedure has a long history, recent quarantine treatments have been approved for primarily tropical and subtropical fruits (USDA-AHIS 2010a, 2010b). Couey et al. (1985) combined ethylene dibromide fumigation with a hot water bath to provide quarantine control of tephritid fruit flies in Hawaiian papayas. Later, a double-dipping procedure, along with selection for fruit maturity, was used for Hawaiian papayas against the same quarantine pests (Couey and Hayes 1986). Hot water immersion is used to control fruit flies in mango from Florida and fruits imported into the USA (Sharp 1986; Sharp and Picho-Martinez 1990; Sharp et al. 1988, 1989a, 1989b, 1989c). Because of the thermal stress placed on the product, this treatment seems more applicable to tropical and subtropical fruits than with other commodities. Sharp (1994a) provided additional discussion on hot water immersions of fresh tropical fruits to control various fruit flies. In Hawaii, hot water immersion has been examined to treat fruit flies in longan, *Dimocarpus longan* (Lour.) Steud. (Follett and Sanxter 2002, Armstrong and Follet 2007), and lychee, *Litchi chinesis* Sonn. (Follett and Sanxter 2003, Armstrong and Follet 2007). Hara et al. (1993) found that hot water immersion at 49°C for 6 min) controlled all mobile life stages of the armored scale, *Pseudaulacaspis cockerelli* (Cooley) (Homoptera: Diaspididae), on leaves of bird of paradise, *Strelitzia reginae Aiton*. Hara et al. (1994) also demonstrated that hot water immersion (49°C for 10 min) would de-infest all mobile stages of the green scale, *Coccus viridis* (Green) (Homptera: Coccidae), on propagative cuttings of cape jasmine, *Gardenia jadminoides* Ellis. Hot water treatments (50°C for 15 min) have now been expanded to include control of the burrowing nematode, *Radopholus similis* (Cobb) Thorne (Tylenchida: Pratylenchidae), on potted bamboo palms, *Chamaedorea seifrizii* Burrent, and fishtail palms, *Caryota mitis* Lour. (Tsang et al. 2003), and on Hawaiian anthuriums, *Anthurium andraeanum* Linden (Tsang et al. 2004).

Crocker and Morgan (1983) used hot water (60°C) baths to control weevils in acorns, but the treatments also reduced seed germination. Morgan and Crocker (1986) later recommended 49°C water baths for 15 min to control weevils in acorns as a more suitable treatment. Kerbel et al. (1985) found peaches were tolerant to some hot water treatments for control of the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae). For other pests, McLaren et al. (1997, 1999) described a commercial scale 2-min hot water bath (50°C) to control the New Zealand flower thrips, *Thrips obscuratus* (Crawford) (Thysanoptera: Thripidae) on apricots, peaches, and nectarines. Shellie and Mangan (2000) compared fruit quality of hot water treatments with forced hot air and vapor heat on mango, papaya, grapefruit, and orange.

Some household pests such as bed bugs, *Cimex lectularius* L. (Homoptera: Cimicidae), can be controlled with hot water. Laundering infested clothes and linens in water >49°C with detergent, followed by 20 min in a standard clothes drier (>60°C) will eliminate all life-stages (USDD 2010).

Hot water baths have been used extensively in the laboratory to determine thermal kinetics of heat treatments. Waddell et al. (1997) compared mortality responses of two Cook Island fruit fly species, *Bactrocera melanotus* (Coquillett) and *Bactrocera xanthodes* (Brown) (Diptera: Tephritidae), by hot water emersions between 43°C and 48°C. In New Zealand, Jones et al. (1995) did similar work with three tortricid species in hot water baths between 39°C and 47°C. In Hawaii, Follett and Sanxter (2001) examined mortality of *Cryptophlebia* spp. (Lepidoptera: Tortricidae) in hot water baths for quarantine control in lychee and longan.

2.3.2. Steam

Chittenden (1897) recommended using steam on the flour mill machinery to control contamination by the Mediterranean flour moth, *Anagast kuehniella* (Zeller) (Lepidoptera: Pyralidae), and reported using 52–60°C for a few hours to kill other grain insects. Howard and Marlatt (1902) suggested using steam to control the carpet beetle, *Anthrenus scrophulariae* (L.) (Coleoptera: Dermestidae), on woollen products. Brodie et al. (2002) developed a 1-h steam treatment against the golden nematode, *Globodera* rostochiensis Wollenweber (Tylenchida: Heteroderidae). Chen and White (2008) recently described a vacuum/steam treatment to control five species of mold on cotton.

Steam was first reportedly used for soil sterilization in 1893 by W.H. Rudd of Greenwood, Illinois, USA, by placing soil in a chamber with perforated steam pipes (Beachley 1937). May (1898) described a procedure for using steam to control nematodes, while Stone and Smith (1989) recommended soil steaming as the most practical method to control nematodes. In South Africa, researchers (Scherffius et al. 1911) compared five thermal methods for sterilizing soil, including a heat–formalin combination, and concluded that pouring boiling water on the soil was the best process. In England, Russell and Petherbridge (1912) examined steam sterilization and found very satisfactory results between 82°C and 100°C. Winston (1913) briefly reported that a steam–formalin treatment was more effective than steam alone against soil pathogens of tomato and potato. Selby and Humbert (1915) described steam-delivery systems to be used in greenhouses. Beinhart (1918) discussed the use of steam to sterilize seed beds for tobacco. Russell (1920) compared the efficacy of steam alone with cresylic acid or formaldehyde treatments, and reported steam to be the most effective against pathogens and wireworms. Hunt and O'Donnell (1922) briefly described that steaming for 75 min can produce about 100°C at a soil depth of 17 cm. Hunt et al. (1925) found that doubling the steam pressure doubled the rate of heat penetration. Smith (1926) demonstrated improved growth of tomatoes after soil steaming. Bewley (1926) presented several designs for steaming soil. Sackett (1927) also described elaborate plans for steaming soil in greenhouses. Newhall (1927) compared different methods of steaming soil in vegetable greenhouses. Falconer (1928) recommended steaming over dry heat ("baking") and chemical application, and provided another steaming design. Bewley (1929) compared steaming to dry heat ("baking"), found baking more destructive to soil colloids, and presented designs for both steaming and baking.

Scheffer (1930) in the state of Washington (USA) used steam to sterilize soil pathogens in a conifer seed bed. Newhall (1930) demonstrated using steam to control a root-knot nematode, *Meloidogyne* spp. (Tylenchida: Heteroderidae), in the greenhouse. In Australia, Magee (1931) described an inverted steam pan system to control soil pathogens of tomatoes. In England, Hinks (1932) reported a new steam plant for soil sterilization and warned that the soil requires three to twelve weeks to recover before planting. Senner (1934) described four methods of soil sterilization using steam and compared the energy requirements for each. Compton (1936) used steam to heat water for sterilizing soil in greenhouses. Beachley (1937) reported on a steam–formaldehyde combination treatment. In Germany, Quantz-Pillnitz (1937) described an improved method of steaming soils by using fodder-steamers.

Considerable work continued in testing, refining, and evaluating steam sterilization through the next 15 years (Johnson 1946; Malowany and Newton 1947; Skillman 1949a, 1949b; Walker and Thompson 1949; Ball 1950, 1953). Van Koot and Wiertz (1947) developed a mathematical model that described thermal death of soil organisms from steam treatments. Baker and Roistacher (1957a, 1957b, 1957c) have written extensively about theory, application, and methodology of soil heat treatments.

Steam is still used to treat soil. Lawson and Horst (1982) discussed how steam controls greenhouse soil pests, gave a comparison of costs for BTUs (British Thermal Unit = 1055 J or 252 Cal) based on oil, gas, and coal as fuels, and for pesticides and fumigants. Runia (1983) described an improved steam delivery system for loam and sandy soils. Bartock (1993) reiterated that steam is more effective and safe for controlling soil pests than dry heat and fumigants. Szmidt et al. (1989) found that steaming perlite substrates resulted in higher crop yields than thermal treatments by dry heat and radio frequency emission.

2.3.3. *Vapor heat*

Like water baths, vapor heat uses moisture (in saturated air) to transfer thermal energy (<100°C) and usually involves air movement and is an old process. Vapor heat was first used in Mexico in 1913 to control the Mexican fruit fly, *Anastrepha ludens* (Loew) (Diptera: Tephritidae) (Latta 1932). Later, vapor heat at 44°C controlled the narcissus bulb fly after 2 hr and other vapor heat procedures were developed to control the Mediterranean fruit fly in Florida citrus (Latta 1932). This technology was applied in California for several types of fruits and vegetables for Mediterranean fruit fly control (Mackie 1931). A similar approach was taken with Texas citrus for fruit fly control (Hawkins 1932).

Vapor heat technology was further developed by Baker (1952) for citrus and is now widely used for papaya, pineapple, bell pepper, eggplant, tomato, and zucchini (USDA 2005). Sinclair and Lindgren (1955) modified vapor heat for California citrus and avocados, and Seo et al. (1974) applied this technology for treatment against the oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae). In Hawaii, Hansen et al. (1992) investigated vapor heat as a treatment against against representative quarantine pests of cut flowers and foliage, but found damage to floral commodities at efficacious levels. In Florida, McCoy et al. (1994) presented a vapor heat treatment against the eggs of the Fuller rose beetle, *Asynonychus godmani* (Crotch) (Coleoptera: Curculionidae). Follett (2004) obtained complete control against life stages of the mealybug, *Maconellicoccus hirsutus* (Green) (Homoptera: Pseudococcidae), with vapor heat at 49°C for 10 min. For more information on vapor heat treatments, see Hallman and Armstrong (1994).

2.3.4. *Dry heat*

These treatments are generally based on maintaining an interior temperature for a prescribed period. As discussed earlier, pests that hide in structures can be controlled by heating the facility. Much of the earliest and most extensive use of heat as a commodity treatment was to control grain insects in the commodity. Thermal treatments against the Angoumois Grain Moth, *Sitotroga cerealella* (Oliver) (Lepidoptera: Gelechiidae), were used in France for stored grains as early as 1792 (Fields and White 2002). By 1883, the French were using machines for heating infested grain (Dean 1911, 1913) whereby 4 h at 49°C was sufficient to kill larvae and pupae of the Angoumois grain moth. In the USA, it was found that grain treated at 49–55°C for a few hours destroyed the immature forms of the red flour beetle, *Tribolium castaneum (Herbst)* F. (Coleoptera: Tenebrionidae), (Lintner 1885). Goodwin (1914) recommended 40–50% relative humidity ("moist heat") when treating grain insects at 48–50°C. Husain and Bhasin (1921) proposed superheating wheat up to 100°C for 30 s to control the khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae); all larvae were dead after 5 h at 50°C. Adults of the rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), and the granary weevil, *Sitophilus granaries* (L.) (Coleoptera: Curculionidae), expired when exposed to 54.5°C for 30 min (Back and Cotton 1924). Grossman (1931) determined that grain corn treated at 50°C for 1 h controlled all life-stages of the Angoumois Grain Moth, the rice weevil, the red flour beetle, the slenderhorned flour beetle, *Gnatocerus maxillosus* (F.) (Coleoptera: Tenebrionidae), and the squarenecked grain beetle, *Cathartus quadricollis* (Guérin-Méeneville) (Coleoptera: Cucujidae). Oosthuizen (1935) provided a thorough discussion of the effect of heat on the confused flour beetle, *Tribolium confusum* Jacqueline du Val (Coleoptera: Tenebrionidae). In Japan at around the same time, Harukawa and associates examined the use of heat to control the Angoumois moth in wheat, including rate of thermal conduction (Harukawa 1941; Harukawa and Kumashiro 1941). Tsuchiya (1943) did similar work on the adult rice weevil.

A second method to control grain pests is to treat the milling and storage equipment and structures. Popenoe (1911) heated a room to 47°C for 30 min to control the Indian meal moth, *Plodia interpunctella* (Hübner) (Lepidoptera: Pyralidae), in stored peanuts. Pepper and Strand (1935) described how heating the structure of a grain mill to 66°C can control grain pests within 24 h. Imholte and Imholte-Tauscher (1999) recommended heating structures or food processing components to 50–60°C for at least one day. Dosland et al. (2006) provided specifications and procedures for heat treating stored product insects. Beckett et al. (2007) reviewed and compared different thermal procedures to treat stored product structures and equipment to control pests.

Another early use of heat for insect control was for inedible commodities, particularly those containing natural fibers and farinaceous compounds. To control omnivorous psocids in habitations and other human structures, Back (1920) recommended heating the room to 60°C for 30 min. Cressman (1933) suggested heating rooms to 60–63°C for 6 h to control the cigarette beetle, *Lasioderma serricorne* (F.) (Coleoptera: Anobiidae), in libraries containing bound, printed books.

Thus, the early approach was often to heat the structure as well as the material being attacked. Sheppard (1984) recounted the measures used in commercial mills and food plants in using heat to control stored-grain pests residing in the infrastructures. Heaps (1988, 1996) described the procedures for eliminating stored product pests hidden in food processing areas. Heaps and Black (1994) delineated the heating requirements to control the confused flour beetle in a food plant mixing area. Menon et al. (2000) promoted the use of heat at or above 50°C to replace methyl bromide fumigation for insect management in mills and other food-processing plants. Mahroof et al. (2003) described the temperature and relative humidity parameters needed to kill the developmental life stages of the red flour beetle in food-processing facilities. Akdoğan et al. (2005) compared two different heating systems, along with contour temperature plots, for stored-product pest control in a pilot flour mill.

The use of dry heat is an attractive alternative to those desiring a method to eliminate structural pests without fumigation. Forbes and Ebeling (1987) compared population mortalities of four pest species often found in buildings [adult German cockroaches, *Blattella germanica* (L.) (Blattodea: Blattellidae); adult confused flour beetles; nymphs of the western drywood termite, *Incisitermes minor* (Hagen) (Isoptera: Kalotermitidae); and adult Argentine ants, *Iridomyrmex humilis* (Mayr) (Hymenoptera: Formicidae)] and obtained complete control for all within 7 min at 54°C; they then provided accounts of thermal treatments of infested rooms in Los Angeles, California, USA, and a house in Miami, Florida, USA. Ebeling et al. (1989) described dry heat treating for powderpost beetles (Coleoptera: Lyctidae) in three historic USDI National Park Service buildings at the Buffalo National River in Arkansas, USA. Ebeling (1994a) reviewed the thermal variables and equipment needed to control structural pests. Quarles (1994) noted that thermal treatments were as effective as conventional fumigations for structural pest control and its costs were decreasing. Ebeling (1994b) found that the heat penetration was inversely related to wood density when applying thermal structural treatments. Quarles (1995) discussed the synergistic effects when boric acid was included with heat in structural pest management. Lewis and Haverty (1996) compared six methods to control the western drywood termite (including dry heat, microwave, and electrocution) and found that dry heat and microwave gave effective results. Nicholson and von Rotberg (1996) described a thermal system to control pests in historical structures as well as museum items. Ebeling (1997) provided additional details of thermal control of pests in structures, including flour mills and cereal plants. Zeichner (1998) gave an overview of the thermal techniques, including microwave, to control the western drywood termite in buildings. All these publications attest that thermal treatments are now accepted as effective control measures against various structural pests.

Commercial thermal treatments for imported wood packaging to control insects, usually 30 min at 56°C throughout the profile, has been approved by Japan, China, New Zealand, Australia, Europe, North America, and most of South America (Anonymous 2005). This treatment is now standard for international trade (FAO 2006). A requirement added more recently is that the packaging must be debarked (FAO 2009). However, Ramsfield et al. (2010) reported that this treatment did not completely control all of the fungi species which they evaluated.

Thermal treatments have been developed for specific wood pests. McCullough et al. (2007) examined heat treatments against the Emerald Ash Borer, *Agrilus planipennis* (Coleoptera: Buprestidae), and found that 50°C for 120 min was necessary to control larvae and prepupae in wood chips. Nzokou et al. (2008) successfully controlled emerald ash borer in logs with a kiln treatment of 65°C throughout for 30 min. Myers et al. (2009) examined oven treatments against the emerald ash borer in firewood and concluded that an internal wood temperature of 60°C for 60 min was the minimum for heat sterilization. Recently, Goebel et al. (2010) have verified that 56°C for 60 min, 2.5 cm deep in firewood, is insufficient to control emerald ash borer.

Dry heat has been effective against stored product pests of grains, nuts, and dried fruits. Dry heat is recommended against the Khapra Beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae) in milled products by using 82.2°C for 7 min and against the root knot nematode (Stout and Roth 1983). Lethal temperature durations have been published for stored product pests (Fields 1992) and insect pests found in museums (Strang 1992). Kirkpatrick and Tilton (1973) obtained $>99\%$ mortality of the rice weevil and the lesser grain borer during a 4-day treatment at 39°C and 43°C, respectively. In India, Battu (1975) computed the temporal–thermal death relationships of Khapra Beetle larvae in wheat. In Australia, Dermott and Evans (1978) obtained almost complete disinfestation within 12 min at 59°C in wheat for all immature life stages of the rice weevil, the lesser grain borer, and the Angoumois grain moth. In examining a continuous-flow fluidized bed heating system for wheat, Evans et al. (1983) established that complete control of the immature stages of the lesser grain borer depended on consistent grain temperatures >65°C for 4 min.

In India, Saxena et al. (1992) subjected pupae of the Khapra beetle, confused flour beetle, and the southern cowpea weevil, *Callosobruchus chinensis* (L.) (Coleoptera: Bruchidae), to durations of 45°C up to three days and found adult sterility, if not suppressed adult formation, at the longest period. Mahroof et al. (2003) determined time–mortality relationships for eggs, neonate larvae, old larvae, pupae, and adults of the red flour beetle. Boina and Subramanyam (2004) measured the thermal susceptibility of all life-stages of the confused flour beetle. Mahroof et al. (2005) determined the adverse effects on fecundity, egg-to-adult survival, and progeny production of the red flour beetle when exposed as 1-day-old pupae and 2-week-old adults to 50°C for 60 min and 39 min, respectively. Subramanyam (2005a) provided additional information about the effect of heat on reproduction of the red flour beetle.

Dry heat can also be used against household pests embedded in structures. The USDD (2010) recommends controlling bed bugs by heating an infested room to >45°C until effective (no time period given). Pereira et al. (2009) developed a thermal death time curve for bed bugs showing 100% mortality from 100 min at 41°C to 1 min at 49°C.

2.3.4. *Forced hot air*

Forced hot air is similar to vapor heat, but does not have the moisture component and is a more recent development (Armstrong et al. 1989). Forced hot air has advanced as a technique because of improvements in temperature and moisture monitoring and in air delivery (Hallman and Armstrong 1994). Hansen et al. (1997) obtained complete control of the banana moth, *Opogona sacchari* (Bojer) (Lepidoptera: Tineidae), on the ornamental *Dracaena fragans* (L.) Ker-Gawl. at 44°C for 30 min without damage to propagation or foliage.

Treatments are being refined for commodities subjected to vapor heat and applied to new commodities. Its disadvantages are the long treatment durations and the sophisticated equipment needed for operation. Not all horticultural commodities are suitable, for example, avocado (Kerbel et al. 1987). Follett and Sanxter (2000), in examining forced hot air as a treatment against fruit flies in rambutan, also reported unacceptable commodity damage.

2.3.5. *High-temperature controlled atmospheres*

Another anaerobic procedure combines forced hot air with an oxygen-poor environment, achieved by replacing oxygen with nitrogen or using high concentrations of carbon dioxide. The mechanism of control is to increase respiration demands for the target pest, as occurs during heating, yet restrict the amount of oxygen available so as to cause suffocation. Besides exchanging gases, sophisticated instrumentation is used, like that employed in the forced hot air system.

The greatest advancement and application of high temperature controlled atmosphere treatments (HTCAs) has been against stored product pests. Many studies on controlled atmospheres targeting stored product pests noted the relationship between temperature and mortality. In examining air-tight storage of grain, Bailey (1965) demonstrated that mortality of Khapra beetle larvae and adults of lesser grain borer, red flour beetle, sawtooth grain beetle, and rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) (Coleoptera: Laemophloeidae), were due to oxygen depletion rather than accumulation of carbon dioxide. Harein and Press (1968) found that increasing the treatment temperature resulted in higher mortality of insects exposed to low oxygen – high carbon dioxide concentrations, and that larvae of the Indian meal moth were more susceptible to the treatment than larvae and adults of the red flour beetle. AliNiazee (1972) reported that susceptibility of red flour beetles and confused flour beetles to anoxia caused by high levels of nitrogen or helium increased with increased temperatures. Storey (1975) also found increased mortality in adults of the rice weevil, lesser grain beetle, red flour beetle, and the sawtoothed grain beetle with increased temperatures under a low-oxygen atmosphere. Storey (1977) concluded that pupae and eggs of the confused flour beetle and the red flour beetle were the most resistant life stages when exposed to low-oxygen atmospheres and that mortality increased with the rise in temperature.

Banks and Annis (1977) provided protocols for controlled atmosphere storage of grain, including necessary temperatures for controlling grain pests. Bailey and Banks (1980), in reviewing the then current low-oxygen procedures to control stored product pests, stated that efficacy is dependent on temperature and gave an example of increased granary weevil mortality with increased temperatures over the same time period. Soderstrom et al. (1986) examined the relationship of low-oxygen atmospheres with temperatures in causing larval and pupal mortality in the Indian meal moth and the navel orangeworm, *Amyelois tranitella* (Walker) (Lepidoptera: Pyralidae). Delate et al. (1990) studied the effect of temperature on mortality due to controlled atmospheres of larvae and adults of the sweetpotato weevil, *Cylas formicarius elegantulus* (Summers) (Coleoptera: Apionidae). Wang et al. (2001a) studied the survivorship of a booklouse, *Liposcelis bostrychophila* Badonnel (Psocoptera: Liposcelididae), a common pest of dry foods, exposed to controlled atmospheres among a range of temperatures, and observed increased mortality at temperstures >27.5°C.

Later studies combined elevated temperatures with controlled atmospheres to improve efficacy. Soderstrom et al. (1992) obtained increased mortality of larvae of the red flour beetle when temperatures ≥ 38°C were combined with carbon dioxide enriched or oxygen deficient atmospheres. Delate et al. (1994) found that a

7-day postharvest heat treatment at 45°C and ≥95% carbon dioxide resulted in total control of the apple twig beetle, *Hypothenemus obscurus* (F.) (Coleoptera: Scolytidae), in Hawaiian macadamia nuts. In Israel, Donahaye et al. (1996) reported on the combined effect of temperature and various low-oxygen atmospheres on mortality of all life stages of the red flour beetle. In Germany, Mbata et al. (1996) examined the mortality of all life-stages of cowpea weevil and a bambara groundnut bruchid, *Callosobruchus subinnotatus* (Pic.) (Coleoptera: Bruchidae), from exposures at 32°C in a complete carbon dioxide atmosphere, and they recorded total mortality for eggs and adults after 24 h. HTCA treatments have now replaced methyl bromide fumigations, particularly in Europe, for pest control of stored food items, spices, grain in silos and ships, furniture, and floorboards (Bergwerff and Vroom 2003).

Studies on HTCA treatments for horticultural crops are of a more recent origin. Early experimental units were based on the forced hot air design (Gaffney and Armstrong 1990; Gaffney et al. 1990; Sharp et al. 1991, Neven and Mitcham 1996). Many HCTA studies for horticultural pests were to control the light-brown apple moth, *Epiphyas postvittana* (Walker) (Lepidoptera: Tortricidae), in New Zealand apples. Among eggs and larvae, Whiting et al. (1991) found that the fifth instar was the most treatment-resistant whereas the first instar was the most susceptible. Dentener et al. (1992) examined the light-brown apple moth along with the longtailed mealybug, *Pseudococcus longispinus* (Targioni-Tozetti) (Homoptera: Pseudococcidae), and found treatment efficacy four times better at 20°C than at 0°C. Whiting et al. (1995) compared mortality from HTCA treatments of the light-brown apple moth to five endemic tortricid species and reported that survivorship increased with increasing oxygen content.

Lay-Lee et al. (1997) investigated HTCA treatments to control the light-brown apple moth and a wheatbug, *Nysius huttoni* White (Hemiptera: Lygaeidae), quarantine pests of apples exported to the USA. A calculated mean mortality of 99% was found at greater than 17 h of treatment. In Australia, Chervin et al. (1998) studied the synergistic properties of the components of HTCA treatment against the light-brown apple moth. Whiting and Hoy (1998) found that mortality of the light-brown apple moth increased logarithmically with exposure time to HTCA treatments. Whiting et al. (1999a) fount that adding tebufenozide to an HTCA system increased efficiency when applied to instars of the same species. Whiting et al. (1999b) proposed combining an HTCA treatment with cold storage at 0°C to control larvae of the light-brown apple moth and brownheaded leafroller, *Ctenopseustis obliquaana* (Walker) (Lepidoptera: Tortricidae).

HTCA methodologies have been applied to codling moth and other horticultural pests. Soderstrom et al. (1991) examined survival of codling moth eggs and adults to different concentrations of carbon dioxide and oxygen. Chervin et al. (1998) examined the additive effects of mild heat at 30°C with low oxygen concentration followed by cold storage at 0°C on survival of fifth instar codling moths. In New Zealand, Potter et al. (1994) subjected adults of the New Zealand flower thrips to HTCA treatments at a range of temperatures (0–20°C) and predicted complete kill after six days of exposure regardless of temperature. Whiting and van den Heuvel (1995) examined the effects of oxygen and carbon dioxide concentrations and temperatures of HTCA treatment to control diapausing adult two-spotted spider mites, *Tetranychus urticiae* Koch (Acari; Tetranychidae). Ahumada et al. (1996) investigated a similar method to control a variety of pests of "Thompson Seedless" grapes and reported encouraging preliminary results. Shellie et al. (1997) used the HTCA treatments to control Mexican fruit fly larvae, but there were also some deleterious effects on fruit quality. Whiting and Hoy (1997) determined treatment parameters of an HTCA treatment against the obscure mealybug, *Pseudococcus affinis* (Maskell) (Homoptera: Pseudococcidae), on apples.

Neven and Mitcham (1996) discussed the development of an HTCA treatment known as *Controlled Atmosphere Temperature Treatment System* (CATTS). Shellie et al. (2001) found that a CATTS procedure suitable against Codling Moth in fresh sweet cherries produced marketable fruits, and Neven (2005) described two CATTS methods using chamber temperatures of 45°C and 47°C, respectively, against the codling moth in fresh sweet cherries. Neven and Rehfield-Ray (2006) demonstrated the efficacy of these treatments against the western cherry fruit fly, *Rhagoletis indifferens* Curran (Diptera: Tephritidae). Obenland and Neipp (2005), in treating nectarines and peaches with a CATTS protocol for codling moth, reported acceptable commercial fruit quality. Neven (2004) provided further discussion of CATTS and other HTCA treatments for fresh commodities.

2.4. Electric fields

Although steam-heating is the standard method for thermal disinfestation of soil, studies have been done using electric current to produce heat. When an electric current is applied to a material, such as soil, internal resistance produces heating. Around 1898, researchers in Massachusetts, USA attempted to electrocute root knot nematodes in soil and were successful when the soil temperature reached 49°C, its thermal death point (Newhall 1955). In England, Viscount Elveden (1921) compared productivity of soils treated with electricity, steam, and flame, and found that electric resistance heating gave better results than steam. In Washington state, USA, entomologist C.F. Doucette demonstrated that soil could be heated with alternating current and showed that the amount of heat generated directly related to the amount of soil moisture (Anonymous 1932). Studies on soil heating using electrical resistance were also done in Holland about 1931 (Newhall 1955), and in Germany using a three-phase circuit (Dix and Rauterberg 1933). After extensive testing, Fee (1933) recommended that resistance heating was more practical than steam for soil sterilization of flats and benches in greenhouses. Tavernetti (1935) designed a cabinet for sterilizing soil on greenhouse benches using electrical current, with soil temperature variations accotrding to differences in soil characteristics, while adjusting voltages was the best method for controlling electrical demand. In Holland, Muyzenberg and Roghair van Rijn (1937) did extensive testing of resistance heating using electricity.

Carney (1932) reported on a method for soil sterilization by using electrical heating elements (dry heat). Horsfall (1935) developed an improved soil sterilizer using electrical heating elements and referred to its advantages over steam. Blauser (1935) also presented a design to sterilize soil using dry heat from electricity. Newhall and Nixon (1935), who compared heating by electrical elements with resistance heating, listed the factors needed for uniform temperature, and they concluded that both these methods were at least as effective as steaming. Newhall (1940) itemized the limitations of resistance heating (including operator safety, high demand on the service line, care in loading the chamber to get uniformity, and the need to increase conductivity by adding an electrolyte solution), while further developing the heating element procedure. Tavernetti (1942) described a continuous process using a screw conveyor and heating elements. The most limiting factor for all these electrical methods was the amount of energy needed to treat a relatively small volume of soil (Newhall 1955).

2.5. *Electromagnetic energies*

2.5.1. *Infrared*

The frequency of the infrared region of the electromagnetic spectrum is from 0.3 to 430 THz, between visible light and microwaves. Infrared radiation is strongly emitted by hot substances and is readily absorbed by living tissue. Thus, it is logical that infrared radiation has been examined as a thermal treatment. Schroeder and Tilton (1961) reported complete control of rice weevils and lesser grain borers with infrared exposures of less than a minute and at mean temperatures of 56°C and 68°C, respectively. Tilton and Schroeder (1963) examined the rate of adult emergence of rice weevils, lesser grain borers, and Angoumois grain moths from rice by temperatures produced by infrared radiation. Kirkpatrick et al. (1972) found greater control of rice weevils with infrared radiation than with microwave exposures. Kirkpatrick and Tilton (1972) measured mortalities of twelve species of stored product beetles in soft winter wheat and obtained >99.5% mortality for all when treated at 65°C for less than a minute. Kirkpatrick (1975a) reported that eggs and early instars of the lesser grain borer and Angoumois grain moth were more resistant to infrared treatments than eggs and early instars of rice weevils. Kirkpatrick (1975b) treated wheat infested with rice weevils and lesser grain borers in bulk with infrared radiation and obtained >93% mortality after exposure to 43.3°C after 24 hours. More recently, Subramanyam (2004, 2005b) reported mortality from flameless catalytic infrared heaters on adults of the sawtoothed grain beetle, rice weevil, red flour beetle, lesser grain borer, and merchant grain beetle, *Oryzaephilus mercator* (Fauvel) (Coleoptera: Silvanidae). However, research and application of infrared technologies have not been popular in recent decades.

2.5.2. *Microwave*

Microwaves have been applied to a wide range of products, from soil and museum artifacts to fresh fruits. However, the most predominant efforts of current microwave technology have been to control pests of grain and stored products (Nelson 1973; Roseberg and Bögl 1987; Nelson et al. 1998; Wang and Tang 2001).

Hamid and Boulanger (1970) described a microwave system to dry wheat and obtained complete control of the confused flour beetle at 65°C for >30 min. While examining a microwave unit for drying grain, Boulanger et al. (1971) reported complete control of larvae and adults of the confused flour Beetle, the granary weevil, and the rusty grain beetle, *Cryptolestes ferrigineus* (Stephens) (Coleoptera: Cucujidae), within 15 min at 45°C. Kirkpatrick et al. (1972) found microwave treatments were less effective than infrared treatments for rice weevils. Kirkpatrick (1975a) found that mature larvae and pupae were more resistant to microwaves than either larvae or eggs of the Angoumois grain moth, rice weevil, and lesser grain borer. Watters (1976) reported that mortality of different life stages of the confused flour beetle exposed to microwaves was a function of time and wheat moisture content. Nelson (1976, 1977) measured the microwave dielectric properties of adult rice weevils and hard red winter wheat. Tilton and Vardell (1982a) obtained >96% control of the Angoumois grain moth, lesser grain borer, rice weevil, and maize weevil, *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae) in rye, corn and wheat after a microwave treatment at a partial vacuum of 35 torr for 10 min. Tilton and Vardell (1982b) went on to describe a pilot-scale microwave/vacuum grain dryer that completely controlled the rice weevil in wheat. Langlinais (1989) demonstrated that the confused flour beetle and the flat grain beetle, *Cryptolestes pusillus* (Schnherr) (Coeloptera: Cucujidae), can be economically controlled with microwave exposures. In Italy, Locatelli and Traversa (1989) found that beetles were more resistant than moths when using microwave treatments of rice, with the lesser grain borer being the most tolerant; and that temperatures had to be greater than 80°C to assure complete control. In Canada, Shayesteh and Barthakur (1996) determined that 80°C, generated by microwaves, was needed to kill the most resistant life stage of the confused flour beetle and Indian meal moth. Using a 4-s microwave exposure, Halverson et al. (1996) treated soft white wheat infested with different life stages of the red flour beetle and the maize weevil and obtained >58°C grain temperatures and $>95\%$ insect mortality. Halverson et al. (2000) provided efficacy data for a microwave applicator against immature life stages of the rice weevil, red flour beetle, and lesser grain borer. Nelson and Payne (1982) described the reduced effectiveness in the control of the pecan weevil, *Curculio carya* (Horn) (Coleoptera: Curculionidae), in pecan nuts while using microwaves. In England, Wilkin and Nelson (1987) used microwaves to kill adult red flour beetles and sawtoothed grain beetles, as well as larvae of the Indian meal moth and the almond moth, *Ephestia cautella* (Walker) (Lepidoptera: Pyralidae), in walnuts at 60°C for 15 min. In Turkey, Baysal et al. (1998) used 90-s microwave exposures to control almond moth on sun-dried figs. A vacuum microwave grain dryer was found to rapidly disinfest product of four stored product insect species (Tilton and Vardell 1982a). Phillips et al. (2001) confronted severe arcing when treating flowing grain, but reported $>99\%$ control of three species of stored product beetles with static infested grain samples when treated with 2.45 GHz at 30 kW.

Investigations into the microwave applications of fresh horticultural commodities have been limited. In tests to control the mango weevil, *Cryptorhynchus mangiferae* (F.) (Coleoptera: Curculionidae), Seo et al. (1970) observed that microwave exposures of 45 s resulted in cooked rind and pulp of treated mangoes. In Spain, Del Estal et al. (1986) found that adults were the most susceptible life stage of the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae), to microwave exposures. Sharpe (1994b) described the equipment used to study the effects of microwaves on grapefruits infested with by the Caribbean fruit fly, *Anastrepha suspense* (Loew) (Diptera: Tephritidae). Sharp et al. (1999) examined the effect of microwaves on mature larvae of the Caribbean fruit fly and concluded that rapid heating imposes serious constraints on the use of heat-induced mortality. Ikediala et al. (1999) obtained higher mortality in third instar codling moth by adding 1–2 days of cold storage after microwave treatments. Wang et al. (2003) found no differential heating of codling moth larvae that had infested walnuts.

Microwaves have been examined for their potential to sterilize soil (Nelson 1996a). Ferriss (1984) found that the microwave treatment of 4 kg of soil for 425 s was a convenient, rapid method of eliminating soil pathogens and, compared with autoclaving or methyl bromide-chloropicrin fumigation, that microwave treatments released less nutrients into the soil, had less of an effect on soil prokaryotes, and resulted in less recolonization by fungi. Diprose et al. (1984) found that microwaves were less effective against the reniform nematode in soil than 1,3-dichloropropene fumigation. Langlinais (1990) obtained some success in treating fire ants, *Solenopsis geminate* (F.) (Hymenoptera: Formicidae), in the field with a 4500-W microwave unit and recommended injecting enhancers to concentrate energy. Nelson (1996a) concluded that microwave methods for field control of soil pests were inappropriate without major technological breakthroughs, because of severe attenuation of microwave energy in soils, the improbability of effective selective heating of target organisms, and the high costs of energy and equipment.

Microwave energy has been explored to treat wood and wood products. Hightower et al. (1974) recommended microwave radiation for raising temperatures to 50°C for controlling exotic beetle larvae in hardwoods imported from Africa and South America. Burdette et al. (1975) conducted tests using microwave energy against beetle larvae in hardwood and concluded that this treatment was economically promising. However, Crocker et al. (1987) found that microwave treatments were unsuccessful against weevils in oak acorns. Lewis and Haverty (1996) compared microwave treatments to five other methods to control the drywood termite and obtained 99% mortality at 4 weeks after treatment. To control the Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae), Fleming et al. (2003) found that microwaves heated wood to the controlling temperature of 60°C within 5 min compared to 123 min from conventional heating, and recommended microwave treatment to eradicate Asian longhorned beetles in solid wood packing materials. Fleming et al. (2004) identified the variables for scaling up a microwave treatment for Asian longhorned beetle control in solid wood packing materials based on moisture content. Fleming et al. (2005) found that wood temperatures >62°C sufficient to control the Asian longhorned beetle and the pine wood nematode, *Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle (Aphelenchida: Parasitaphelenchidae). Henin et al. (2008), in examining microwave treatments to control the house longhorned beetle, *Hylotrupes bajulus* L. (Coleoptera: Cerambycidae), concluded that wood surface temperature >60°C guaranteed lethal conditions within wood, regardless of moisture content. Nzokou et al. (2008) examined microwave to control emerald ash borer, but concluded that the kiln treatment was better and commended further research with radio frequency.

Microwaves have also been applied to other non-food items. Reagan et al. (1980) used a conventional kitchen microwave unit to kill eggs, larvae, and adult stages of the webbing clothes moth, *Tineola bisselliella* (Hummel) (Lepidoptera: Tineidae), and found that 4 min provided full control for all stages. Hall (1981) discussed treating herbarium specimens with microwaves as an alternative to fumigation for controlling larvae and adults of the larger cabinet beetle, *Trogoderma inclusum* LeConte (Coleoptera: Dermestidae), and the drugstore beetle, *Stegobium paniceum* (L.) (Coleoptera: Anobiidae). Philbrick (1984) studied seed viability and slight morphological changes in specimens when microwaves were used for herbarium pest control. As with the other applications, microwaves worked best on dried subjects.

2.5.3. *Radio frequency*

Three radio frequencies are recognized in the USA for industrial purposes: 13.56 ± 0.067 MHz, 27.12 ± 0.60 MHz and 40.68 ± 0.020 MHz (Wang et al., 2001b). Radio frequencies generate internal heat by resistance from the very rapid change in molecular polarity. The advantages of radio frequency heating are that it is very fast, can penetrate deep into the target material because of its longer wavelength, may produce possible differential heating between the product and the pest, and does not produce toxic residues.

The lethal thermal effects on insects caused by radio frequency exposures were first reported by Lutz (1927) and Headlee and Burdette (1929). McKinley and Charles (1930) killed all adults of a parasitoid wasp, *Braconhebetor* (Say) (Hymenoptera: Braconidae), with 30-s exposures of radio frequency 86 MHz. McLennan (1931) investigated heating from induced fields caused by radio frequency exposures on objects of different conductivities, dielectric properties and shapes, all which are important for applying radio frequency technology to a wide range of commodities. Hadjinicolaou (1931) attributed the death of a variety of stored product pests, after exposure to high frequency radio waves, to internal heat generated within the body of each insect. Whitney (1932) attributed insect death from radio frequency exposures to overheating. Davis (1933) described how radio frequency energy can kill stored product pests. Pyenson (1933) examined the protective properties of various shielding materials, such as cloth and cereals, surrounding insects, and concluded that insects could be effectively killed when treated in dry soil, woody materials and paper, clothes, tobacco, seeds and grains, flours, cereal breakfast foods, and nuts because these items have low moisture content. Shaw and Galvin (1949) examined heating characteristics of vegetative tissues including those from potato, carrot, apple, and peach. Thomas (1952) produced a comprehensive review of the use of high-frequency to control pests in a wide assortment of substrates, from seeds and grains to fruits and vegetables, and attributed the major lethal agent to heat.

Headlee (1931) did much of the early investigations involving the relationships of radio frequency exposures on insects, and discovered that radio frequency exposures caused differential injury between insects and their host plants. In developing methods to control soil insects, he also found that the ability of radio frequency to heat soils was associated with moisture content (Headlee 1932; Headlee and Jobbins 1936), and related the internal heating of insects by radio frequency energy to its lethal effects (Headlee 1933). Headlee and Jobbins (1938) concluded that the heat generated by radio frequency exposures that were necessary to kill all of the life stages of the Japanese beetle, *Popilla japonica* Newman (Coleoptera: Scarabaeidae), will also damage the roots of the host plant.

Studies on electromagnetic energy treatments were conducted against pests other than arthropods, particularly in soils. Eglitis et al. (1956) described two types of high frequency energy generators for soil pasteurization. Mai (1958) used dielectric heating to eliminate encysted Golden Nematode larvae, *Globodera rostochiensis* (Wollenwber) (Tylenchida: Heteroderidae), from burlap potato bags. Baker and Fuller (1969) concluded that commercial microwave treatment for soil pathogens was impractical and they listed some of the impediments involved, including poorly uniform heating. Eglitis and Johnson (1970) were unsuccessful in controlling soil pathogens by radio frequency treatments. However, O'Bannon and Good (1971) reported complete control against a root-knot nematode, *Meloidogyne incognita* (Kofoid & White) Chitwood (Tylenchida: Heteroderidae), in potting soil. Seaman and Wallen (1967) examined the effect of radio frequency exposures on seed pathogens.

Radio frequency heating techniques were applied as early as the 1930s to grain. Mouromtseff (1933) used a specially constructed oscillator to kill ''wheat weevils'' without damaging the grain, which was attributed to dielectric differences. Ulrey (1936) described using two ultra-high frequency, high power oscillators in series to double the power. Kuznetzova (1937) showed that mature larvae of the granary weevil were more resistant to high frequency electric currents and that adults outside the grain were more susceptible than those within grain. In Idaho, Iritani and Woodbury (1954) found an inverse relationship between seed size and seed heat tolerance with radio frequency heating, and demonstrated treatment efficacy against the pea weevil, *Bruchus pisorum* (L.) (Coleoptera: Bruchidae). Soderholm (1957) described a dielectric heater for controlling insects in grain.

Nelson and Kantack (1966) discussed the physical factors that influence the effectiveness of radio frequency heating for controlling grain insects in wheat, noting that lower grain moisture increased treatment efficacy. They also ranked the pests in order of increasing resistance to control, with rice and granary weevils being the most susceptible, followed by the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.) (Coleoptera: Cucujidae), confused and red flour beetles, dermestids, and the cadelle, *Tenebriodes mauritanicus* (L.) (Coleoptera: Trogositidae). The lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae), was found to be the most tolerant. Nelson and Charity (1972) identified the 10–100 MHz frequency range as the best for controlling Rice Weevils. Nelson and Stetson (1974) determined that the 39 MHz frequency was a better band than the 2450 MHz frequency for controlling rice weevils in wheat.

Physiological examinations after radio frequency exposures demonstrated behavioral and physical changes to insects. Mickey and Heller (1964) found that organisms moved either parallel or perpendicular, but not randomly, to wave direction when exposed to electromagnetic fields. Furthermore, Mickey (1963) showed that radio frequency energy induced genetic crossing-over in germ cells of a vinegar fly, *Drosophila* sp. (Diptera: Drosophilidae). Rai et al. (1971) observed abnormal morphological changes in the adult yellow mealworm beetle, *Tenebrio molitor* L. (Coleoptera: Tenebrionidae), from larval exposures to radio frequency fields.

Other than investigations with grain insects (Nelson 1996b; Nelson and Kantack 1966), radio frequency received little attention after the middle of the last century. Early reviews are provided by Ark and Parry (1940), Webber et al., (1946), Frings (1952), and Thomas (1952). Later commentaries are given by Whitney et al. (1961), and Watters (1962).

Recent efforts at pest control using radio frequency have targeted pests of fresh fruits and nuts. Ikediala et al. (2000) described the dielectric properties of apples and codling moth larvae. Wang et al. (2001c) modeled internal fruit temperatures from radio frequency electromagnetic heating and compared these to those produced by hot air and hot water treatments. Mitcham et al. (2004) demonstrated the efficacy of radio frequency treatments against three pests (codling moth, navel orangeworm, and Indian Meal Moth) within whole walnuts. Wang and Tang (2004) proposed using radio frequency heating as a postharvest method to control insect pests in nuts and other stored products. Wang et al. (2005) developed a mathematical model that described internal heating of in-shell walnuts for insect pest control. In 2005, the commercial feasibility of radio frequency methodologies to control stored product pests of walnuts was demonstrated at a walnut packing house (Wang et al. 2005). Mirhoseini et al. (2009) tested the efficacy of 13.56, 27.12, and 40.68 MHz against the confused flour bettle and the rice weevil, and they reported that pest control potency and intensity increased as radio frequency increased.

Recent research has also investigated radio frequency treatments to control fungi in wood. Tubajika et al. (2005, 2007) examined efficacy using a 40-kW radio frequency oven to destroy wood decay and sapstain fungi, and they reported fungus inhibition at 60–70°C for 2 min. They further noted that moisture loss in the wood may be an important factor in radio frequency treatments.

2.6. Solar

Solar energy has been investigated as a thermal treatment. Compared to the other methods, this is a relatively recent procedure. Grooshevoy et al. (1941) anticipated that solar energy could provide sufficient heat to destroy pathogens in tobacco seed beds. However, Yeomans (1952) who examined different forms of radiant energy, including radio frequency, did not mention solar energy and concluded that infrared radiation was impractical because of high cost and poor penetration. Grinstein et al. (1979) used polyethylene sheets to raise soil temperatures by solar heating, which is the procedure now frequently used.

Very little has been done using solar energy to control insects. Although the approach is simple and has potential for long-term storage in rural areas and in developing countries, there are problems with temperature control and maintaining consistency. Most work with solar heat treatments of commodities has targeted bruchid pests of seeds. Murdock and Shade (1991) showed that the cowpea weevil, *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae), can be eliminated from cowpea stores by solar heating. Kitch et al. (1992) described a simple plastic solar heater to disinfest cowpeas of the Cowpea Weevil in northern Cameroon. In Zimbabwe, Chinwada and Giga (1996) demonstrated that solar heating by the use of black plastic sheets was effective in controlling two bean bruchids, *Zabrotes subfasciatus* (Boheman) and *Acanthoscelides obtectus* (Say) (Coleoptera: Bruchidae). In Cameroon, Ntoukam et al. (1997) controlled the cowpea weevil in cowpea seeds using a solar heater. Songa and Rono (1998) reviewed several methods of bruchid control in beans and reported that Kenyan farmers prefer sunning and sieving for pest control because of its safety, low cost, and maintenance of grain cleanliness. In Nigeria, Arogba et al. (1998) recommended sun-drying cowpeas on wooden surfaces to reduce insect and mold infection. Ugwu et al. (1999) found that cowpea control was greater on wooden surfaces rather than corrugated iron sheets or cement surfaces. In India, Chauham and Ghaffar (2002) developed a solar heating method using clear polyethylene bags for control of *Callosobruchus* spp. in pigeonpea.

Solar heating has been used to control other stored product and fruit pests. Nakayama et al. (1983) found that black plastic in solar heaters was better than clear plastic and aluminum foil for controlling the hide beetle, *Dermestes maculatus* De Geer (Coleoptera: Dermestidae), from dried mullet, the Indianmeal moth from peaches, and the merchant grain beetle, *Oryzaephilus mercator* (Fauvel) (Coleoptera: Cucujidae), from oatmeal. McFarlane (1989) proposed using solar cabinets, where 50°C was the critical temperature, to control the larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae), in maize cobs. Shorey et al. (1989) demonstrated that solar heating reduced infestation by Nitidulid beetles (larvae and adults) while enhancing the ripening and drying of commercial figs. Higbee et al. (2001) proposed covering fruit bins with clear plastic to increase temperatures to eliminate diapausing larvae of the codling moth. Baskin (2001) described a solar bagging method to eliminate insect infestations in artifacts. Pearce (2003) developed an inexpensive solar oven and Brokerhof (2003) developed a solar tent to control insect infestations in museum pieces.

Soil sterilization by solar heating, or "solarization," has become a popular inexpensive treatment. This is usually done by covering the substrate with a type of plastic tarp. Katan (1981a, 1981b) reviewed solarization for controlling soil pathogens, mites, and insects. Pullman and DeVay (1977) used clear 4-ml polyethylene plastic to reduce *Verticillium dahliae* propogaules, obtaining maximum temperatures of 55°C and 43°C at depths of 5 cm and 15 cm, respectively. Pullman et al. (1981a) field-tested clear polyethylene tarps against a range of soil pathogens, including *V. dahliae*, and developed a mathematical model to describe thermal death (Pullman et al. 1981b). Ashworth and Gaona (1982) reduced *V. dahliae* in moist soil within 24 hours when 45°C was obtained under clear polyethylene. In California, Morgan et al. (1991) significantly reduced soil inoculum density of *V. dahliae* by using a clear polyethylene tarpaulin.

Other soil pests have been controlled using solarization. Egley (1983) described controlling various weeds using soil solarization under clear polyethylene and obtained 69°C at 1.3 cm soil depth for up to 4 hours at mid-afternoon. Overman (1985) found the lowest nematode populations with solarization when compared with three other off-season methods. In Florida, USA, McSorley and Parrado (1986) used clear polyethylene to control the reniform nematode, *Rotylenchulus reniformis* Linford & Oliveira (Tylenchida: Hoplolaimidae). In South Africa, Barbercheck and von Broembsen (1986) reduced the populations of five species of plant-parasitic nematodes by using clear polyethylene sheets. Ramirez-Villapudua and Munnecke (1987, 1988) controlled cabbage yellow pathogens, *Fusarium oxysporum* f. sp. *conglutinans*, by using solarization. Stevens et al. (1988) examined soil solarization with clear plastic sheets to control soil pests of grapes. Liebman (1994) proposed using soil solarization with clear plastic to control soil pests of California strawberries. In Florida, soil solarization using differently colored plastics was examined (Chellemi et al. 1997a; Chellemi 1998) to replace methyl bromide fumigation to control soil pests, particularly root-knot nematodes, of pepper and several cucurbits. Chellemia et al. (1997b) found no difference in the incidence of Fusarium wilt and spiral nematodes, *Helicotylenchus* spp. (Tylenchida: Hoplolaimidae), in soil treated with solarization or methyl bromide fumigation. The United Nations (Anonymous 2003) recommended soil solarization as an alternative to methyl bromide fumigation. The most severe limitation of soil sterilization by solarization is the reduced sunlight during the winter months, which impacts those areas producing winter crops.

3. Conclusions and future developments

Since these early attempts to control insects by thermal methods, the applicable technologies have progressed in mechanical design and theories. Advances in instrumentation now provides accurate temperature measurements and other treatment variables. Techniques have improved in precision and replication. The extensive history of the development of these treatments may provide pointers to the development of new forms and prevent duplication of previous attempts. The future application of thermal treatments is promising because of the extensive methods that can be used to produce and control heat.

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