Application of Radiant Energy in Pest Management[1]

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ABSTRACT

All forms of radiation, from the radio waves to high-energy X-rays, have potential applications in an integrated pest management program, including insect disinfestation and detection and microbial control and sterilization. Because radiowave, microwave, and infrared energies produce significant amounts of heat, they may also be used to cook and dry food products. Ultraviolet light and visible light are used in light traps for insects, and ultraviolet is of sufficiently great energy to be of value in controlling airborne or surface microorganisms. Proven potential exists for the use of radio frequencies, microwaves, and infrared and ultraviolet light in insect disinfestation. However, commercial use has not been extensive. Gamma rays, X-rays, and accelerated electrons have commercial applications for insect disinfestation and microbiological sterilization of many products, including foods. Because their modes of action are very different, irradiation with microwaves or infrared light followed or preceded by irradiation with gamma rays, X-rays, or accelerated electrons may produce greater results than predicted for two treatments with the same radiation form.

The proper application of electromagnetic energy can provide an important part of an integrated pest management (IPM) program. IPM is defined as a method of determining whether pest (microorganisms, insects, rodents, birds) suppression treatments are needed, when they are needed, where they are needed, and what mix of treatments are required to obtain the best solution for pest control, based on predicted economic, ecological, and sociological consequences. The applied treatments may involve any combination of physical, chemical, and biological methods. Ideally, combinations of methods that produce synergistic results will be chosen. The physical methods involving various forms of electromagnetic energy will be discussed here, primarily for managers seeking new integrated pest management methods.

At least eight forms of electromagnetic energy may be used to control pests. The major forms of electromagnetic energy of interest are radio waves, microwaves, infrared light, visible light, ultraviolet light, X-rays, gamma rays, and accelerated electrons (1–3), as shown in Table I. They form an energy spectrum ranging from very low to very high (Fig. 1), and all of the more useful forms of energy, with the exception of gamma rays, are machine generated (Table I). Beta rays are generated by radioactive decay (1) but are described here only in connection with electron beams, as natural beta ray-energy is too low to be of significance in most aspects of an IPM program. The principal modes of action reflect the energy level of radiation forms (1–11), ranging from heat generation to disruption of chemical bonds and potentially atomic changes (Fig. 1, Tables I–III). Electrons, negatively charged particles with masses

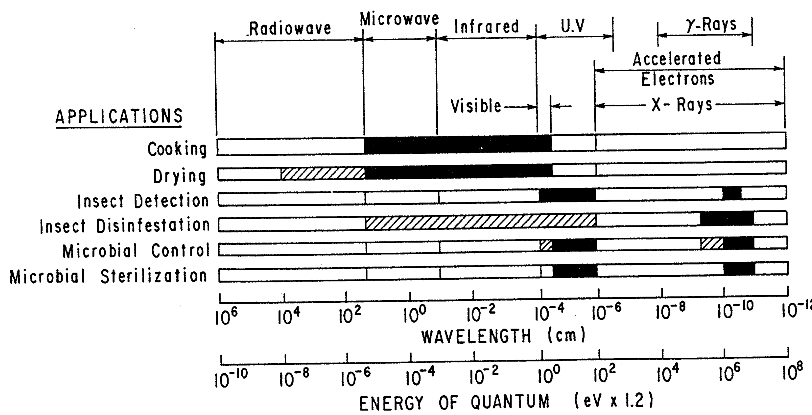

Fig. 1. Energy spectrum.

Table I. Source and Physical Properties of Radiant Energy

Energy Type	Source	Wavelength Range	Energy (Electron Volts)
Radio wave[a]	Piezoelectric-, ferroelectric-, or magnetostrive-transducers	$0.1–3 \times 10^6$ cm	$4.1 \times 10^{-11}–1.2 \times 10^{-3}_{eV}$
Microwave[a]	Magnetron or klystron	0.06–30 cm	$2.1–4{,}100 \times 10^{-3}_{eV}$
Infrared[a]	Incandescent objects	$8 \times 10^{-5}–0.06$ cm	$1.6_{eV}–2.1 \times 10^{-3}_{eV}$
Visible light[a]	Light source	$4–8 \times 10^{-5}$ cm	$1.6–3.1_{eV}$
Ultraviolet light[b]	Mercury or deuterium lamps	$5–400 \times 10^{-7}$ cm	$8.2–250_{eV}$
Beta ray[c]	Radioactive decay	...	$8–13{,}000 \times 10^{6}_{eV}$
Electron beam[c]	Machine generated	...	Almost no limit (limited to 10 MeV for use with food)
Gamma ray[c]	Radioactive decay	$10^{-8}–10^{-11}$ cm	$1.2 \times 10^{4}–1.2 \times 10^{7}_{eV}$
X-ray (Roentgen ray)[c]	Machine generated	$10^{-6}–10^{-12}$ cm	$1.2 \times 10^{2}–1.20 \times 10^{8}_{eV}$

[a] From Daniels, F., and Alberty, R. A. (2).
[b] From Koller, L. R. (3).
[c] From Lapp, R. E., and Andrews, H. L. (1).

[1] Reference to brand or firm names does not constitute endorsement by the U.S. Department of Agriculture over others of a similar nature not mentioned.

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of 1/1840 that of the hydrogen atom and integral parts of neutral atoms (1), can be accelerated to produce atomic changes which occur at an approximate energy level of 10.4 million electron volts (MeV). X-rays with sufficient energy to cause atomic changes can also be generated. Thus, the energy level of electrons is restricted to a maximum of 10 MeV and that of X-rays is restricted to a maximum of 5 MeV for food applications. The major, but not the only, effect of radio waves, microwaves, and infrared light on living organisms is the generation of heat which, if severe enough, can be fatal. The energy of the photon is inversely proportional to the wavelength, which means that the shorter the wavelength, the greater the potential effect on matter. Starting with visible light and increasing with shorter wavelength, radiation affects chemical bonds. High-energy X-rays and electrons may have sufficient energies to cause nuclear changes. Heat is generated by the absorption of all forms of electromagnetic energy, and even radio and microwaves may generate mutations. Thus, the interactions of these energy forms and biological matter may be complex. Because energy forms from opposite ends of the spectrum have predominantly different modes of action, the use of microwave energy or infrared energy, for example, with ionizing radiation, such as gamma rays, may produce results that are greater than would be expected. Treatments with electromagnetic energy have one obvious advantage over traditional chemical methods in that there are no potentially toxic residues, but these same treatments suffer from the lack of residual protection of the product. (One should not assume, however, that because there are no residual chemicals the treatments may not have resulted in the formation of potentially toxic products in a food. This is especialy true of any process which results in significant heating of the product.)

Energy Types, Applications, and Limitations

Radio Frequency. Because radio frequency (RF)-energy produces heat in materials which absorb it, it may be used for insect control. Radio waves are electromagnetic waves with frequencies of 15,000–10,000 cycles per second. RF-energy has been of particular interest because insects tend to absorb the energy more readily than grains and because it has great penetrating power. This means that insects can be killed by being exposed to RF fields for only a few seconds without damaging the surrounding grain (12–15). The heating rate is directly proportional to the field intensity and frequency. The greater the moisture content, the greater the heating. Adult insects tend to be more susceptible to RF exposure than are the immature forms. The mortality rate depends primarily on the final temperature obtained. RF heating was used in at least one case over a period of several years for the disinfestation of feed bags so that they could be reused.

Microwave. Microwave energies (high-frequency electromagnetic radiation with wavelengths of 1 mm–50 cm) are primarily used in the food industry for defrosting frozen foods and cooking. Most of the heating is achieved through dielectric heating of polar molecules (Table II). Basic principles of microwave radiation and its use in food processing may be found elsewhere (4,5,16–22). The major cause of death of microbes or insects exposed to microwave energy may be expected to be the result of heating (Table III). However, abnormalities have been noted in adult *Tenebrio molitor* after the pupae were exposed to pulsed radar (23), and mammals exposed to microwaves have been found to have altered immune systems (24–26). Thus, potentially, there are effects other than simple heating involved.

One of the most promising uses of microwave energies is for the control of stored-product insects because in addition to controlling the insects, they also dry the grain. Tilton and Vardell (27) have evaluated a pilot plant-scale

Table II. Physical, Chemical Interaction of Radiant Energy with Matter

Energy Type	Interaction	Penetration
Microwave[a,b,c]	Rotational energy changes at molecular level, dielectric heating of polar compounds	Great
Infrared[a,d]	Rotational and/or vibrational molecular transitions, heating	Low
Visible light[d]	Chemical changes, heating, bleaching	Low
Ultraviolet light[a,d,e]	Excitation of electrons; ionizations; chemical reactions	Low
Beta ray and electron beam[f]	Ionization (loss of 35 eV for each ion pair formed in air); free radical generation	Low, approx. 0.48 cm in H_2O/MeV
Gamma ray[f]	Photoelectric ionization; free radical generation	High half value; thickness in water is 9.8 cm^{-1} for 1 MeV
X-ray (Roentgen ray)[f]	Compton effect; pair production	

[a] From Daniels, F., and Alberty, R. A. (2).
[b] From Copson, D. A. (4).
[c] From Goldblith, S. A. (5).
[d] From Sanderson, J. E., and Hulburt, E. D. (6).
[e] From Buttolph, L. J. (7).
[f] From Lapp, R. E., and Andrews, H. L. (1).

Table III. Biological Effects of Radiant Energy

Energy Type	Possible Biological Effect(s)	Factors Altering Degree of Effect
Microwave[a,b,c]	Heat; cellular death	Electric field strength, frequency, dielectric properties
Infrared[d,e]	Heat, energy selectively absorbed by pigments	Incident power, time, irradiated area, or volume
Visible light[d,e]	Energy selectively absorbed by pigments; stimulation of photosynthesis; photosensitization	Time, surface area, color
Ultraviolet light[e,f]	Energy selectively absorbed by nucleic acids and proteins; genetic effects; photosensitization	Incident power, time irradiated area, or volume
Beta ray and electron beam[g,h]	Unselective ionizations; free radical reactions; direct and/or indirect genetic effects; cell death; virus inactivation	Temperature; atmosphere; type of food; fat and/or water content
Gamma ray and X-ray[g,h]	Unselective ionizations; free radical reactions; direct and/or indirect genetic effects; cell death; virus inactivation	Temperature; atmosphere; type of food; fat and/or water content

[a] From Copson, D. A. (4).
[b] From D'Ambrosio, G., et al (8).
[c] From Stuchly, M. A. (9).
[d] From Sanderson, J. E., and Hulburt, E. D. (6).
[e] From Seliger, H. H., and McEhoy, W. D. (10).
[f] From Buttolph, L. J. (7).
[g] From Lapp, R. E., and Andrews, H. L. (1).
[h] From Wang, C. P., and Brynjolfsson, A. (11).

microwave vacuum drying unit for use in controlling *Rhyzopertha dominica* F. and *Sitophilus oryzae* L. infesting wheat. Complete control was achieved at a partial vacuum of 35 torr. The microwave energies were not defined. Kirkpatrick et al (28) compared the use of gamma, infrared, microwave, and a combination of gamma with either infrared or microwave energies in controlling *R. dominica* in soft winter wheat. The authors reported reductions of emergence of 54, 55, and 42% for gamma, infrared, and microwave treatments, respectively. The combination of gamma and infrared or microwave produced significantly greater reductions of 95 and 89%, respectively (27–32). Other stored-product insects may be susceptible to microwave radiation—for example, *T. confusum* in wheat and flour (33), *T. molitor* in flour (8,34), *Sitophilus granarius* in pasta (8), *Oryzaephilus surinamensis* L. and *Plodia interpunctella* Hb. in grain, flour, and rolled oats (35,36), and the cigarette beetle (*Lasioderma serricorne* F.) and tobacco moth (*Ephestia elutella* Hb.) (37).

The use of microwave and radio frequency-energies is not limited to insect control. Heald et al (38) have reported that the reniform nematode and common purslane weed can be controlled in soils treated with UHF electromagnetic fields. A prototype microwave weed killer was patented in 1975 for controlling weeds, nematodes, certain fungi, and soil-borne insect pests (39). Internal molds were reduced in freshly harvested corn kernels by microwave heating from 100% to less than 20% (40). The potential for microwave vacuum treatment as a means of drying grain is well documented (41).

Infrared Radiation. The application of infrared energy (electromagnetic radiation with a wavelength longer than that of the visible region but shorter than that of microwaves) in cooking is obvious, but its application in an IPM program is perhaps less obvious. One of these applications is the use of infrared CO_2 analyzers to detect insects in foods. Work at the USDA Stored-Product Insects Research and Development Laboratory showed that infrared energy could detect a single larvae of *Ephestia cautella* Wlk. in one out of 10 lb of dates and hidden infestations of wheat grain (42,43). Infrared emitter-detectors have proven of value for actograph studies of single insects (44).

Infrared radiation has been successfully used for controlling stored-product insects in wheat. Kirkpatrick (45) demonstrated a 99% kill of *S. oryzae* and 93% kill of *R. dominica* by infrared radiation which raised the wheat temperature to 48.6°C. Natural infestations of stored wheat of *S. oryzae, R. dominica, Cryptolestes pusillus* Schonh., and *Tribolinum castaneum* Hbst. were controlled by raising the temperature to 55°C (28). Cogburn (46) discovered that sublethal doses of infrared radiation did not inhibit reproductions of rice weevils, lesser grain borers, or Angoumois grain moths. Recent studies (47) show that combining infrared radiation with a partial vacuum (25 torr) is significantly more effective than infrared radiation without vacuum in controlling the lesser grain borer *R. dominica* and the rice weevil *S. oryzae*. The practical value of such treatment remains to be fully investigated. For example, how much of the grain can be penetrated by a given heating source? What factors will control the temperature increase of grain in other than a single layer? As previously described, gamma, infrared, and microwave radiations may produce synergistic effects when combined. Recently developed infrared lasers (48,49) may have application in IPM programs.

Visible Light. Most effects of sunlight of interest in an IPM program are actually related to either the infrared or the ultraviolet regions of the spectrum. However, we should not forget that many food products, ranging from fish to raisins, are dehydrated using solar radiation, and solar radiation can be focused to achieve much higher temperatures suitable for insect disinfestation of such products as dried fish and grains (50). The use of the light traps in detection programs is based on the common observation that moths are attracted to a flame. The response of the insect depends on the species and the wavelength of the light (51). Kirkpatrick et al (52) found that the Indianmeal moth preferred green light, rather than ultraviolet and green together. Brower and Cline (53) observed that significantly more *Trichogramma pretiosum* and *T. evanescens* responded to ultraviolet rather than to white light traps. Light traps remain a very useful part of a detection program.

Ultraviolet Light. Ultraviolet radiation (with wavelengths shorter than 4,000Å) is used primarily for disinfection of surfaces and air. Ultraviolet can penetrate only approximately 100 μm of materials with the density of water and, like other forms of radiant energy, depends on the type of organism, the temperature, the humidity, the nature and size of particles carrying the microorganisms, and the intensity of the radiation (54). The mutagenic potential and mechanisms of ultraviolet radiation have been fully exploited in microbiology (7) both for control and to produce mutant organisms with altered physiological properties. The genetic and cytological effects of ultraviolet radiation on organisms above the microbial level have been reviewed by Swanson and Sadler (55). Evidence was presented for both cytological and mutational effects in insects and plants; 99.9% of ultraviolet energy was reportedly absorbed by adult *Drosophila* before it reached the germ plasm. As with microbial studies, the effectiveness of a given dose was directly related to the absorption spectrum for nucleic acids.

Ultraviolet light has not been used for controlling insects. One relatively common application is the use of light as an insect attractant (56). Stuben (57) reported that ultraviolet (365 nm) flashes lasting 0.0002 sec significantly increased mortality of *Musca domestica.* The flies were most susceptible on the first day after emergence. A more significant reduction in progeny occurred when infrared radiation was used. Mihailescu et al (58) compared the efficacy of treating garlic with ultraviolet radiation, infrared radiation, or hot air to control nematodes. Bruce (59) and Bruce and Lum (60) recently reinvestigated the possibility of using ultraviolet radiation for insect control. They noted differences in the sensitivity of the Indianmeal moth eggs of different ages. Both the larvae and pupae were also sensitive to exposure to ultraviolet radiation. The researchers used ultraviolet light to control the acarive parasite of stored-product insects *Pyemotes tritici* in insectaries. An important aspect of the use of ultraviolet light for insect or other pest control is the phenomenon known as photoreactivation. Organisms exposed to ultraviolet radiation in the dark and then kept in the dark suffer more than do organisms exposed in the presence of white light or exposed to white light after ultraviolet irradiation (60).

Ionizing Radiation. By definition, ionizing radiation is energetic enough to strip electrons from molecules or atoms and consists of fast-moving subatomic particles or electromagnetic waves. The removal of an electron leaves the molecule or atom in an excited or ionized state. The ionized molecules react almost instantly with one another and with other molecules, producing new substances (radiolytic products). The usual result is unstable secondary products, such as free radicals and peroxides, which spread the reaction of the original ionization. By definition, radiolytic (not radioactive) products are products that are produced uniquely upon radiation (rare) or more typically increase in amount during radiation in a dose-related manner. Gamma rays, X-rays, beta particles, electrons, protons, neutrons, and alpha particles all produce ionizations, but only electrons, gamma rays, and X-rays are of potential value in food irradiation. Alpha particles and beta particles have very limited penetration and are, therefore, of very limited practical value. Neutrons are not suitable for food irradiation because they may induce radioactivity. Electrons, gamma rays, and X-rays are of potential interest in an IPM program. Each of these radiations has particular advantages and disadvantages which depend at least in part on the application for which it is to be used.

Definitions: Ionizing Radiation

Curie (C_i): the amount of radioactive material yielding 3.7×10^{10} disintegrations per second; the basic unit of radioactivity measurement and originally based on the number of disintegrations from 1 g of radium.

Electron volt (eV): the energy gained by an electron when it is accelerated to a potential of one volt.

Roentgen (r): the quantity of radiation required to produce ions equivalent to one electrostatic unit when absorbed by a cubic centimeter of dry air at standard temperature and pressure; equivalent to the absorption of 83.8 erg/g of air.

Rad: an absorbed dose of ionizing radiation sufficient to liberate 100 erg of energy into each gram of tissue through which the radiation passes.

Roentgen equivalent physical (rep): an attempt to define dosage of radiation for materials other than air; originally defined as equivalent to 83 erg/g, but later redefined as 93 erg/g for tissue and other biological materials.

Gray (Gy): an absorbed dose of ionizing radiation liberating 1J of energy per kilogram of matter through which the radiation passes; 1 Gy = 100 rad = 0.1 krad; 10kGy = 1 Mrad.

Radappertization: exposure of food in hermetically sealed packaging to ionizing radiation doses sufficient to kill all organisms of food spoilage or public health significance; in practice the 12D concept is applied and a dose sufficient to reduce the number of viable *C. botulinum* spores by a factor of 10^{12} is used; analogous to canning.

Radicidation: exposure of food to ionizing radiation doses sufficient to kill all nonsporeforming pathogens; analogous to pasteurization.

Radurization: exposure of food to doses sufficient to reduce microbial or insect populations to delay onset of spoilage.

The industrially important ionizing radiations are of three types: gamma radiations, X-rays, and accelerated electron beams. X-rays are of minor importance because of their cost. They are generated as secondary radiation when a metal target is bombarded by a beam of accelerated electrons. The efficiency of this conversion is rarely greater than 5%, making it preferable to use the electron beam directly. The choice between gamma and electron beam depends on the application and the limitations of each type of radiation. The energy of both gamma radiation and accelerated electrons must be limited if the process is going to involve a food product. That limit is approximately 5 MeV for gamma radiations and 10 MeV for accelerated electrons. Greater energies can induce radioactivity in the material being irradiated.

Isotope sources are limited by the requirement that the maximum energy of their gamma radiations must not exceed 5 MeV and by the requirement that neutrons not be emitted. Thus, the most practical isotopes meeting the energy requirement and also availability requirements are cobalt 60 and cesium 137. The major advantage of gamma radiation is its extreme penetration. There is, in fact, no theoretical limit to that penetrating ability, and shielding materials are calibrated in half-values, referring to the mass required to reduce the energy level by one-half. The choice between the use of cobalt 60 or cesium 137 depends primarily on cost, even though cobalt 60 has greater energy. The use of radioisotopes in amounts useful for IPM or food irradiation requires specialized techniques and elaborate precautions to protect personnel within and outside of the plant. Jarrett discusses these factors in detail (61). The requirements for shielding and the necessity to provide complete security for the storage of the radioisotopes means that it is very difficult to design a mobile radiation source. This tends to limit the use of cobalt 60 or cesium 137 to fixed sites with a very high annual processing volume to be economically attractive.

The advantage of electron beam sources is that they may be turned on or off at will by the operator. They are also far more portable than isotope sources. Rambler has described the characteristics of electron beam generators (62). Electron accelerators are basically of two types, linear or cyclic. If the electron is accelerated along a line of sight trajectory with energy added along the path, the machine is a linear accelerator; a good example is the Van de Graaff accelerator. Cyclic machines use radio frequency potentials to accelerate the electrons. The electron in such equipment is accelerated in a circular path through a voltage trajectory. The radio frequency generators are based on microwave generators, such as the magnetron or klystron, which are found in radar installations throughout the world. Thus, the technology of such devices is very advanced. The choice between linear or cyclic instruments depends on the energy requirement of the application. High-energy beams of several MeV are best generated by a linear accelerator, such as the Linac, which uses radio frequencies to achieve sufficient energies. Intermediate energies of less than 3 MeV are produced when machines, such as the Dynamitron, are used. At even lower energies, broad-beam instruments offer several advantages.

The penetration of an electron beam depends on the accelerating voltage and density of the target material. According to Richards (54), the maximum depth of penetration is defined by the following equation:

$$R_m = \frac{0.542 \times 10^{-6}\ V - 0.133}{p},$$

where V = accelerating potential and p = specific gravity of target material.

The electron beam instruments during operation must be properly shielded but, unlike isotope radiation sources, they may be turned off. They do have requirements for cooling and ventilation and a high-voltage, high-capacity power source.

The development of electron beam instrumentation will continue at a rapid pace because of industrial demand. These instruments are used extensively for the sterilization of medical supplies, curing of coatings on metal and wood, cross-linking of polyethylene, and curing of polyesters.

The potential applications of ionizing radiation for the food industry are extensive. Radicidation and radurization may be used for spices, fish and shell fish, and meat and poultry; radappertization may be used for nonrefrigerated sterilized diets, for the military and the space program, for patients with damaged immune systems, and for animal feeds and moist pet foods; and ionizing radiation may also be used as an insecticide for grain and fruit and to extend the shelf-life of fruits and vegetables. The research supporting the potential, as well as the limitations, have been reviewed by many authors (63–68).

The value of ionizing radiation for insect disinfestation, extension of shelf-life, and control of microbial contaminants is well documented (69). Many spices, such as black pepper, caraway, coriander, ginger, marjoram, and tumeric, may be highly contaminated by bacteria and fungi. Aerobic plate counts of 80–100 million bacteria and 100–10,000 mold spores per gram of spice are typical (70). They may also be infested with insects. From a public health standpoint, contamination with bacteria and fungal spores represents the potential hazard. This contamination probably presents little problem in the home, where the food product is not held for more than a few hours. The potential health hazard results when foods are prepared in central plants and delivered over relatively long distances, presenting a potential opportunity for bacterial growth. An example is a processed meat product, which may contain 0.1–1% by weight of spice. The potential aerobic plate count would be 10^5–10^6 per gram of product because of the added spice.

Vajdi and Pereira (71) compared the efficacy of ethylene oxide to ionizing radiation treatment of spices. Their study showed that gamma irradiation (approx. 1.6 Mrad) was more effective than either ethylene oxide or microwave treatments. The ethylene oxide treatment reduced the oil content of the spices and affected the color of paprika. Microwave treatment was not effective.

Several investigators have reported changes in the flavoring characteristics of spices after ionizing radiation treatments. Tjaberg et al (72) did not observe changes in the quality of black pepper at doses below 1 Mrad but did note changes at greater dose levels. White pepper was not altered significantly by doses of up to 4.5 Mrad. Josimović did not observe qualitative changes in irradiated pepper, but quantitative changes in aqueous extracts occurred even below 1 Mrad, though piperine was resistant to ionizing radiation (73). A dose-dependent increase in hydroxy carbonyls was discovered. Some of the changes observed in spices following treatment with ionizing radiation could be reduced or eliminated by using cryogenic temperatures and/or controlling the atmosphere during treatment. The Josimović study is typical of many research studies in that the treatments took place at ambient temperature (not stated) in the presence of air and at a dose rate of 1 Mrad per hour. Thus, the maximum dose required 5 hr and the minimum dose only 15 min. None of the studies reviewed by Farkas (69) indicated a problem in the wholesomeness of irradiated spices. The U.S. Food and Drug Administration published a final rule on June 19, 1984, (74), permitting the use of sources of gamma radiation to control insects and microorganisms in spices and vegetable seasonings at doses not to exceed 10 kGy (1 Mrad). Farkas (69) described several reasons that ionizing radiation treatments of spices would have special economic advantages. Thus, immediate use of the rule permitting the use of doses up to 3 Mrad may be expected.

The recent concerns over the use of chlorinated hydrocarbon fumigants, especially ethylene dibromide, may provide the necessary economic incentives to make use of ionizing radiation for insect disinfestation of grain attractive for some applications. Tilton and Burditt (32) and the Council for Agricultural Science and Technology (75) have reviewed potential applications of ionizing radiation to insect disinfestation of grain and have concluded that because many insect species may be in a commodity, to be effective, an ionizing radiation dose must kill or sterilize the most resistant species present. This is further complicated by the effects of age, metamorphic stage, sex, strain, temperature, type of radiation, and dose rate on the sensitivity of each species of insect. The *Lepidoptera* tended to be more resistant to ionizing radiation than the *Coleoptera*, but there were also substantial differences between species (32). These authors concluded that a dose of 50 krad would control beetles and immature stages of moths and although a few of the adult moths might be fertile, their offspring could be expected to be sterile.

Following treatment with ionizing radiation, the remaining insects ate less. Brower and Tilton (76) found a dose-related reduction in the amount of wheat consumed by *S. oryzae* and *R. dominica* and concluded that the amount of damage caused by live but sterile insects in bulk grain probably would not represent a significant problem. Several other researchers have reported similar results (32). The combination of gamma irradiation with infrared or microwave treatments reportedly produces synergistic results (32).

Lorenz (67) reviewed the extensive data on the wholesomeness of irradiated grains. The wholesomeness studies were generally done at doses far exceeding those which would be used for insect disinfestation, yet studies with both mammals and nonmammals failed to indicate significant decreased nutritional value or toxicity. The use of ionizing radiation to control fungi in grain requires doses sufficient to affect the quality of the grain. The data upon which Lorenz based his conclusions was obtained before 1975 and without control of temperature or atmosphere during the irradiation treatments.

Lorenz (67), Tilton et al (77), and Tilton (78,79), reviewed the economics of grain irradiation. In the United States, regulations have permitted irradiation of wheat and wheat flour since 1963, but none has been irradiated. The primary reason is thought to be economic. As long as they were effective, low-cost fumigants were readily available, and ionizing radiation was not economically attractive. The present ban on the use of ethylene dibromide in the United States may have drastically altered the economics. Another incompletely explored area concerns the use of electron beam radiation sources, rather than cobalt 60 or cesium 137 sources. The results obtained with electron accelerators for grain irradiation in Mexico (80) should be considered before grain irradiation facilities are designed. Tilton and Burditt (32) found that because a high-velocity air stream would be used to move grain through an electron beam, the force of the impact would help kill the insects. The use of X-rays for inspection of grains for hidden insect infestation has been automated (81).

The next major IPM application for ionizing radiation is for insect disinfestation of fruits. Though the use of ionizing radiation for the control of insects on or in fruits was proposed by Balock in 1956 (82), the process is used only experimentally. The comments concerning existing fumigants and economics of grain irradiation also apply to fruits. The major differences are in the sensitivity of the fruit itself to radiation damage. This subject was reviewed by Tilton and Burditt (32), Burditt (83), the Council for Agricultural Science and Technology (84), and Beyers et al (85).

Burditt reported that the calculated dose required to kill 99.99% of adult Mediterranean fruit flies ws 3.4 krad for 2-day-old eggs and 3.5 krad for 6-day-old larvae. Pupae of the Mediterranean fruit fly required 128.8 krad at 10 days of age. The overall conclusion was that a dose of 13 krad would kill 99.99% of the fruit flies infesting papayas. Recently, Jésüs et al (86) reported that both eggs and larvae of *Ceratitus capitata* wied (Mediterranean fruit fly) could be destroyed in oranges with gamma radiation doses of 40–60 krad without damaging the fruit. A dose of 80 krad, however, damaged the peel. Moy (87) reported the results of tests with lemons (var. Eudreka), and oranges (var. Navel), following irradiation at 30–100 krad during storage at 6°C for 4 wk and then at 21°C for two more weeks. No significant differences in aroma, flavor, and texture were detected between irradiated and unirradiated fruits. In some studies, lemons were reportedly fairly sensitive to ionizing radiation. Moy (87) reported that Hawaii-grown papayas irradiated at 75–100 krad were firmer than fumigated papayas and had a significantly different flesh color, which was attributed to delayed ripening of the irradiated fruit. Rigney (88) reported that the life cycle of the Queensland fruit fly, *Docus tryseni*, could be broken by treating either oranges or avocados at a dose of 7.5 krad. Rigney (88) examined several fruits irradiated at doses of 7.5–22.5 krad and did not find obvious damage in Valencia oranges, table grapes, apples, pears, and tomatoes. Avocados showed an increase in vascular browning of the fruit. The effects of ionizing radiation on postharvest ripening and senescence of fruits were reviewed by Akamine and Moy (89). The effect(s) of atmosphere and temperature control should be considered. Shrikhande and Kaewubon (90) reported that high CO_2 during irradiation suppressed aerobic postirradiation C_2H_4 production and respiration. When CO_2 was applied after irradiation, it minimized chlorophyll and ascorbic acid loss and delayed physiological disorders in lemons on storage.

The many other potential uses of ionizing radiation treatments of food products extend from insect disinfestation of dried fish products to the sterilization of foods. These have been reviewed by many authors (63,68).

Lewis (91) recently estimated the cost of insect disinfestation of grapefruit, using ionizing radiation, to be comparable to that of ethylene dibromide. Trichina control with ionizing radiation was estimated to cost 0.1–0.4 cents/lb. Nelson (92) estimated the cost factor to be 3–4 cents/bu for the treatment of grain and cereal products with RF energy in a practical application. At the time that the cost estimate was made, 1974, general opinion was that considerable improvements in the efficiency of the technology would be required to make it competitive with chemical control techniques. Further savings may be obtained by using synergistic treatments. The potential pest management and/or product improvement benefits which may be obtained by using electromagnetic energies are amply shown by research studies. The manager is still the one to find the best method or combination of methods that will result in the most economical and effective pest control system.

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