Journal of Stored Products Research 52 (2013) 36–41

Contents lists available at SciVerse ScienceDirect

Journal of Stored Products Research

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

Control of stored product pests by ionizing radiation

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A R T I C L E I N F O

Article history:
Accepted 9 October 2012

Keywords:
Irradiation
Food irradiation
Storage pests
Pest control
Pest management

A B S T R A C T

Food irradiation for prevention of food-borne illness and disinfestation of commodities of pests is increasing in a number of countries. The goal of this review is to analyze the literature and current use of irradiation to control stored product pests and suggest research to optimize its potential. Doses to prevent reproduction of stored product pests range from 0.05 kGy for *Tenebrio molitor* L. to 0.45 kGy for *Sitotroga cereallela* (Olivier). Small but increasing amounts of grains and pulses are being irradiated in the world today especially in Asia. At least 33 countries permit irradiation of some stored products with 14 countries permitting it for all stored products. Ways in which stored product irradiation research and application may influence other uses of irradiation technology are also discussed. Deactivation of weed seeds might be an area of stored product phytosanitation where irradiation would have an advantage over other measures.

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1. Introduction

Ionizing radiation is used to address various pest problems: 1) The sterile insect technique (SIT) is used to eradicate pests from regions or maintain low pest population levels (Dyck et al., 2005). Factory-reared pests are reproductively sterilized using radiation and released into pest-infested areas to mate with native populations to prevent successful reproduction. The numbers of released pests must overwhelm native populations for SIT to succeed. 2) Phytosanitary irradiation (PI) prevents development and/or reproduction of regulated pests so that regulated articles can be shipped out of regulated areas (Hallman, 2011). For example, citrus fruit exported to the United States from Mexico is irradiated at 150 Gy to prevent the introduction of tephritid fruit flies. 3) Host/prey of parasites and predators are irradiated to arrest their development to facilitate in vivo rearing for augmentative biological control and in other areas of biological control (Hendrichs et al., 2009). It is currently used in parasite release programs in Guatemala, Mexico and Pakistan against Lepidoptera attacking sugar cane and tephritid fruit flies. 4) Irradiation is used to suppress pest populations in stored products when the products are moved (Salimov et al., 2000).

The goal of this review is to analyze the literature and current use of irradiation to control stored product pests and suggest research to optimize its potential. Ways in which stored product irradiation research and application may influence other uses of irradiation technology are also discussed.

2. Nature of ionizing radiation

Ionizing radiation in the form of electromagnetic radiance or high-energy particles creates ions by breaking chemical bonds. The ionizing portion of the electromagnetic spectrum comprises visible light and shorter wavelengths, although visible light ionizes only certain chemicals, e.g., chlorophyll which is ionized to initiate photosynthesis. Ionizing ultraviolet light (wavelengths of 10–400 nm, photon energies of 3–124 eV) has been researched as a surface treatment for grain and to control stored product pests (Faruki et al., 2007). Gamma rays from the isotopes cobalt-60 (1.17 and 1.33 MeV) and cesium-137 (0.66 MeV) may be used for food. Cobalt-60 is bred from standard (nonradioactive) cobalt (atomic weight 58.9) via neutron irradiation. It has a half-life of 5.27 years and decays to standard nickel. Cesium-137 is a fission product of uranium and plutonium and is recovered when processing spent nuclear fuel. It has a half-life of 30.07 years and decays to barium-137 m. Although cesium-137 can be legally used in food irradiation it is not done commercially, and because it is soluble in water, its availability has been strictly regulated and it will probably not be used in food irradiation.

Linear accelerators produce electrons and X-rays. Electrons are high-energy particles which can be used for food irradiation at energy levels up to 10 MeV. An electron beam (e-beam) directed at a heavy metal, such as tantalum or gold, will give off X-rays, and energies up to 7.5 MeV are allowed for food irradiation. At best

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0022-474X/$ – see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.jspr.2012.10.001

~ 14% of the energy from an e-beam is converted to X-rays with the rest given off as heat. The energy levels emitted by all of these sources are below those that could lead to radioactivity in food.

Irradiation, whether by isotopes or machine sources (e-beam or X-ray), has the same mode of action: the gamma rays, X-rays, or electrons knock electrons out of their orbits, creating ions and radicals. The free electrons collide with further electrons resulting in an electron shower. The ions and radicals cause further damage to large organic molecules such as DNA stopping development of irradiated organisms. Indeed, the secondary damage caused by ions and radicals produced by the electron shower may cause more damage to organic molecules than the primary radiation itself.

In organisms, radiation most easily affects sites of ongoing cell division, which in the adult insect include the gonads and midgut. At minimal doses that stop the functions of these organs insects will not reproduce and will cease feeding because the midgut cannot process food.

3. Historical application and reviews of irradiation for stored product pest control

Soon after ionizing radiation was discovered in the late 19th century it was found that organisms could be reproductively sterilized with relatively low doses that showed no other gross effects to the organisms (Hunter, 1912). Irradiation as a commercial insect control technique was applied for the first time in 1929 to cigars to control *Lasioderma serricorne* although the X-ray machine used turned out to be unsuitable for continuous processing (Diehl, 1995).

Watters (1968) reviewed the literature on stored product pest irradiation and concluded that the technology was an important, effective, safe technique for maintaining shelf life of stored products. A dose of 0.5 kGy would be necessary to stop reproduction of all stored product pests although many species (especially Coleoptera) could be controlled with lower doses.

Tilton (1974) arrived at similar conclusions: a dose of 0.5 kGy would control virtually all stored product pests by preventing their reproduction instead of providing acute mortality, which would require much higher doses. He further concluded that even though insects would be alive for some time after irradiation at 0.5 kGy their feeding was greatly reduced, thus, further damage would be minimal. Lepidoptera were harder to control than Coleoptera, with bruchids requiring the lowest doses for stored product pests.

Tilton (1974) reasoned that irradiation of bulk grain was not economical because of the high cost of facility construction and the logistics of passing grains through an irradiation system. At the time (1960's) industry had a serious problem with infestation of wheat flour and it was thought that irradiation could be a solution, but an integrated system of controlling pests in flour consisting of more pest-resistant facilities, improved pesticides, better sanitation and other types of physical controls alleviated that problem by the early 1970's removing the urgency for irradiation of flour.

The largest and longest use of irradiation to control insects was the annual treatment of 400,000 tons of grain imported by the Soviet Union at the Ukrainian port of Odessa which began in 1980 and continued until 2007. The system could treat 400 tons of grain per hour with 0.2–0.4 kGy. During the latter years of operation the amount of grain irradiated at Odessa dropped to 70,000 tons/yr because grain was being imported at other ports in the region after the dissolution of the Soviet Union.

Brower and Tilton (1985) noted that although most stored product pests are cosmopolitan, some, e.g., *Trogoderma granarium* Everts, *Prostephanus truncatus* (Horn), *Corcyra cephalonica* (Stainton), and some bruchids and ptinids, are not cosmopolitan and they recommended the use of irradiation as a phytosanitary treatment against these pests.

Recent comprehensive reviews of stored product pest management mention irradiation. Phillips (2006) concluded that ionizing radiation is not practical for major food industries because of the high start-up costs and negative public perception. It is further concluded that “virtually none of the branded food manufacturers would currently consider adopting ionizing irradiation when only a small percentage of the population would accept food treated in that way.” High start-up costs may impede the development of new food irradiation facilities, but they are being built regardless. Within the past year three new facilities for phytosanitary irradiation have been built in Mexico, Thailand and Vietnam and numerous facilities for other types of food irradiation are being built worldwide.

While it may be true that branded food manufacturers would not currently consider adopting irradiation, it is not true that only a small percentage of the population accept irradiated food; e.g., studies consistently show that the majority of US consumers would buy irradiated food (Eustice and Bruhn, 2006). Large industries with brand names to defend may not be at the forefront of technological change perceived as controversial or risky (Kihlstrom and Laffont, 1979). Often smaller businesses with less to lose but much to gain are the pioneers of technological adoption; large industry adopts when the technology is shown to be profitable and safe. This is how commercial irradiation of fresh fruits and vegetables occurred (Sinco, 2001). A potential problem may arise when an industry is so dominated by a few large corporations that smaller firms that may be potentially less averse to risk based on perceptions essentially do not exist.

Phillips and Throne (2010) list three objections to stored product irradiation: 1) public concerns about the safety of facilities using radioactive isotopes, 2) misperception that irradiated food becomes radioactive, 3) zero tolerance for live insects in treated product by importing countries and the public at large. These objections are mainly based on perceptions; as such the solutions are based on education. Eustice and Bruhn (2006) show that factual education about food irradiation increases public acceptance. Regarding the concern with radioactive isotopes, food irradiation facilities are protected by abundant safeguards, and the use of machine sources (e-beam and X-ray) entirely removes any risk posed by the presence of radioactive isotopes.

The concern about finding live insects in irradiated product was also faced by plant regulatory organizations regarding phytosanitary irradiation. At the doses recommended for insect control irradiation does not provide acute mortality, although the insects will cease feeding, not reproduce and usually die sooner than if they were not irradiated. The plant regulatory community developed protocols to accept live insects during inspection and today the presence of live insects in product that has been documented to be properly irradiated is acceptable. Public antipathy toward live insects in stored products should not be an issue because stored products that are so infested that the public notices will not be accepted whether the pests are dead or alive. Industry cannot tolerate obvious pest infestations. Indeed, live insects have very rarely been found in the 17 years that irradiation has been used as a phytosanitary treatment. This is not to say that live insects do not exist on these shipments, only that their occurrence is lower than the degree of resolution of the effort to find them.

The current extreme caution displayed by many in the food management industries regarding the use of irradiation to solve food problems (e.g., food-borne pathogens, phytosanitation, stored-product protection) may be traced to food safety scandals beginning in the late 1980s. Although people had died every year due to food-borne pathogens no mass poisonings had been documented in the US for about 60 years until 1985 when a highly publicized listeria contamination of cheese in Los Angeles killed 28 people (including 10 neonates) and resulted in 20 miscarriages

(Linnan et al., 1988). In 1989 intense media focus on the potential cancer risk of consuming apple products from apples treated with daminozide (Alar) began an era of increased scrutiny of food production and mistrust of food additives and novel food science technologies (Herrmann et al., 1997). Further publicized cases of mass food poisonings and controversial food production technologies have kept food safety in the public's awareness, although it is ironic that a technique that could readily reduce the number of food poisoning cases (irradiation) could be suspect itself.

Although there have been no food safety scandals related to food irradiation because the process has been amply demonstrated to be safe for humans and livestock that eat irradiated products (WHO, 1999), food irradiation may elicit initial negative impulses from some people before they learn the facts about the process (Eustice and Bruhn, 2006). In some countries (e.g., US) food irradiation suffers an illogical disadvantage compared with other demonstrated safe but controversial technologies because irradiated foods must be labeled as such while foods that have been fumigated or foods from plants genetically modified using molecular techniques, for example, need not be labeled. Of course, if irradiation was readily viewed as a positive food technology labeling would not be a controversial issue but a source of reassurance.

Considerable research has been done on measuring the effect of irradiation on grains, pulses, and their products. At the doses required for insect control few negative effects have been reported (Gao et al., 2004; Hasan and Khan, 1998; Li et al., 2007; Watters, 1968; Watters and MacQueen, 1967). Seeds for planting should not be irradiated because they will not grow normally.

4. Current use of irradiation of stored products

The largest use of food irradiation worldwide today is for spices with >185,600 tons irradiated each year (Kume et al., 2009). The primary reason for irradiation of spices is to control disease-causing microorganisms; any insects present are readily killed by the high doses used (5–10 kGy). In stored products where the objective is to control insects far lower doses (0.05–0.45 kGy) can prevent insects from completing development or reproducing.

Irradiation is approved for stored product use in at least 33 countries today (Table 1). Fourteen countries have approved irradiation of all stored products. However, few of these countries have commercially irradiated stored products. Food irradiation is increasing significantly in Asia. In 2005 in Indonesia 334 tons of grains were irradiated for insect control and in China 4000 tons of beans and grains were irradiated for the same purpose with amounts increasing annually (Kume et al., 2009). China has >100 irradiation facilities and is building more (Peng, 2008). It may be noted that China has had highly publicized problems with food contamination in recent years and may view irradiation as part of the solution to those problems stemming from biological contamination. Rice is currently irradiated in India. Loaharanu (1994) summarized uses of food irradiation and reported that Bangladesh began irradiating pulses in 1986 and the Ivory Coast was building a facility for that purpose. Cuba began irradiating dried beans in 1987, and Croatia and Vietnam were irradiating rice. The amounts or time periods for these uses of food irradiation were not given. Marcotte (2000) reported that grains and pulses were irradiated in China, France, Indonesia, South Africa, and Thailand without giving specifics on reasons, doses, or amounts. It is difficult to get statistics on food irradiation that is not done to satisfy regulatory demands because the information is proprietary and industry may not want to divulge it because of perceived controversy. The European Community does collect data on food irradiation among members and in the last year available (2010) no grain, pulses or their products were reported irradiated, although member countries irradiated a variety of other foodstuffs, e.g., Belgium, France and The Netherlands irradiated >8400 metric tons of mostly frog legs and poultry (EC, 2012).

Table 1
Clearances for irradiation of stored products for pest disinfestation.

Country	Products	Maximum dose (kGy)
Algeria	Cereals, milled products of cereals	10
Argentina	Nuts, dried fruits, vegetables	1
Bangladesh	Any stored product	1
Belgium	Cereals, pulses	1
Brazil	Any stored product	1
Canada	Wheat, wheat products	0.75
Chile	Cocoa beans, rice, wheat, wheat products	1
China	Rice, wheat	0.6
China	Beans	0.2
China	Nuts, dried fruits	0.4
Costa Rica	Cocoa beans, rice, wheat, wheat products	1
Croatia	Cereals, pulses, dried fruits	1
Cuba	Cocoa beans	0.5
Cuba	Sesame seed, milled cocoa	2
Czech Republic	Cereals, milled products of cereals, dried fruits	1
Czech Republic	Pulses	10
France	Dried fruits, pulses	1
Ghana	Any stored product	1
India	Wheat, wheat products, rice, pulses	1
India	Dates, figs, raisins	0.75
Indonesia	Cereals, dried fruits	1
Israel	Any stored product	1
Republic of Korea	Chestnut	0.25
Republic of Korea	Cereals, pulses and their milled products	5
Mexico	Any stored product	10
Netherlands	Pulses, cereal flakes, dried fruits	1
Paraguay	Any stored product	1
Peru	Any stored product	1
Philippines	Any stored product	1
Russia	Corn, wheat	0.3
Russia	Rice	0.7
Saudi Arabia	Any stored product	1
South Africa	Any stored product	1
Syria	Any stored product	1
Thailand	Rice, wheat, wheat products, dried jujuba	1
Tunisia	Pulses, dried fruit	1
Turkey	Any stored product	1
Ukraine	Corn, wheat	0.3
Ukraine	Rice	0.7
United States	Wheat, wheat flour	0.5
Vietnam	Any stored product	1
Zambia	Any stored product	1

5. Potential uses of irradiation on stored products

The current process of harmonization of international trade standards in agricultural products is creating new challenges, some involving quarantine pests. A quarantine pest may be present in a country that has a quarantine against it but not widely distributed and under official control (IPPC, 2012). Discussions on how this harmonization of regulations is affecting countries and their populations, both developed and developing, and commercial enterprises involved in all aspects of trade are ongoing and will most likely take some unexpected turns (Henson and Loader, 2001; Maertens and Swinnen, 2009). Solutions to some of these challenges might involve irradiation of stored products and it is in the interests of harmonized trade to have potential solutions to trade barriers available.

Without identifying them specifically Halverson and Nablo (2000) mention that there are several niche applications of stored product irradiation that are viable alternatives to conventional pesticides. Because the cost (including logistical steps) of irradiating stored products is relatively high compared with alternatives such as fumigation, for irradiation to be viable for stored products they should be of relatively high value and amenable to irradiation compared with alternative techniques. Because of increased restrictions on methyl bromide use, potential problems with pest resistance to hydrogen phosphide, and difficulty in getting new fumigants registered for use on foods, irradiation may have an increased role in stored product protection. Costs and logistics in application of radiation, therefore, might better be compared with non-fumigant alternatives, such as cold disinfestation by natural aeration and refrigeration.

A key reason why irradiation has been adopted for phytosanitary treatment of fresh commodities is because it is generally less damaging to fresh commodities than alternative temperature and fumigation treatments (Hallman, 2011). Indeed, some irradiated fruits (e.g., rambutan) tolerate no other commercial phytosanitary treatment. Largely durable, stored products are generally tolerant of temperature and fumigation treatments to kill pests, thus irradiation does not have the comparative advantage of greater commodity tolerance.

6. Research needs

Some recent research continues to use acute mortality as the criterion for efficacy of irradiation. For most uses of irradiation to control insects, including stored products, this is unnecessary and can lead to adverse quality outcomes from the excessive doses applied to achieve high levels of acute mortality. Prevention of reproduction is an adequate criterion for efficacy of irradiation.

Reproduction of stored product Coleoptera can be prevented with doses ranging from a low of 0.05 kGy for some species to a high of 0.4 kGy for *Palorus subdrepressus* (Wollaston) (Table 2). It would be advantageous to validate this dose for *P. subdrepressus* because it is largely responsible for the generic phytosanitary dose for all insects except pupae and adult Lepidoptera being set at 0.4 kGy when a lower dose might suffice (Hallman, 2012). Although *P. subdrepressus* is not a quarantine pest data from all available insects are used in developing generic treatments because they serve as representatives for their respective groups.

Studies done 46 years ago indicated that *Plodia interpunctella* and *S. cerealella* adults required >1 kGy to prevent reproduction (Cogburn et al., 1966). If this was the case a generic treatment for all stages of Lepidoptera would require a relatively high dose compared with other arthropods. Hallman and Phillips (2008) found that the dose to prevent reproduction for adults of these two Lepidoptera could be lowered to 0.35 and 0.45 kGy, respectively (Table 2). A dose of ~0.45 kGy would probably prevent reproduction of adult Lepidoptera.

Factors that might affect efficacy of irradiation include oxygen concentration, host, temperature, dose rate, and pest phenotype (Hallman et al., 2010). Research is needed to determine if any of these factors are of concern with stored products and, if so, how to compensate.

Some studies have been done with electron energies as low as 60–80 keV (Imamura et al., 2004a; Hasan et al., 2006). At these low energies penetration is reduced to single layers of grains or seeds and commercial application would require systems that could consistently produce that arrangement. Advantages are less shielding required due to the low energy of the electrons and less damage to the commodity because the dose absorbed would be uniform (Imamura et al., 2004b). When irradiation is applied using higher energies to thicker streams of grain those nearer the source will receive higher than required doses in order to get the minimum dose required for efficacy to grains farther from the source.

Although few stored product insects are of quarantine concern fungi and especially weed seeds have become significant barriers to trade in grain (USWA, 2011) and seed for bird feeding. Given the impossibility of removing all weed seeds from grain and the great difficulty in potentially identifying weed seeds during export inspection many weed seeds in exported grain may be suspect of being invasive species. Irradiation is ideally suited to preventing the growth of plants from seed at the relatively low doses in the range used for insect control. The advantages are that no viable alternative to removing the threat of invasive species via weed seeds is presently imaginable, weed seed deactivation can be accomplished while the grain is being loaded for export, and there is no risk of reinfestation after weed seed-infested grain is irradiated. Ships are loaded at the rate of about 600 tons/h at each loading spout and the e-beam system at Odessa treated up to 400 tons/h. Higher capacity irradiation systems are feasible. Research on doses to deactivate weed seeds would need to be conducted because the research has not been done to any extent.

Table 2
Doses to the adult (most radiotolerant stage) to prevent reproduction of stored product pests.

Order, Species	Dose (kGy)	Reference
Acari		
Acarus siro	0.3	Burkholder et al. (1966)
Tyrophagus putrescentiae	0.3	Ignatowicz (1997)
Coleoptera		
Attagenus unicolor	0.13	Tilton et al. (1966b)
Callosobruchus chinensis	0.08	Supawan et al. (2005)
C. maculatus	0.1	Dongre et al. (1997)
Cathartus quadricollis	0.2	Brower (1974b)
Dermestes maculatus	0.3	Seal and Tilton (1986)
Gibbium psylloides	0.3	Brower and Scott (1972)
Gnathocerus maxillosus	0.2	Brower (1974a)
Lasioderma serricorne	0.1	Imai et al. (2006)
Oryzaephilus surinamensis	0.125	Tunçbilek (1997)
Palorus subdrepressus	0.4	Brower (1973a)
Prostephanus truncatus	0.06	Ignatowicz (2004)
Rhyzopertha dominica	0.115	Matin and Hooper (1974)
Sitophagus hololeptoides	0.1	Brower (1975)
Sitophilus granarius	0.1	Aldryhim and Adam (1999)
S. oryzae	≤0.132	Tilton et al. (1966a)
S. zeamais	0.1	Brown et al. (1972)
Stegobium paniceum	0.05	Harwalkar et al. (1995)
Tenebrio molitor	0.05	Brower (1973b)
T. obscurus	0.1	Brower (1973b)
Tenebriodes mauritanicus	0.05	Brower and Mahany (1973)
Trogoderma glabrum	0.175	Tilton et al. (1966b)
T. granarium	0.2	Gao et al. (2004)
T. inclusum	0.2	Brower and Tilton (1972)
T. variabile	0.1	Brower and Tilton (1972)
Tribolium castaneum	0.16	Gochangco et al. (2004)
T. confusum	0.175	Tilton et al. (1966a)
Lepidoptera		
Cadra cautella	0.3	Cogburn et al. (1973)
Corcyra cephalonica	0.1	Huque (1971)
Ephestia elutella	0.3	Brower (1979)
Ephestia kuehniella	0.3	Ayvaz and Tunçbilek$ (2006)
Plodia interpunctella	0.35	Hallman and Phillips (2008)
Sitotroga cereallela	0.45	Hallman and Phillips (2008)
Psocoptera		
Liposcelis bostrychophila	0.3	Wang et al. (2009)
L. entomophila	0.3	Wang et al. (2010)
L. paeta	0.3	Wang et al. (2012)

Acknowledgments

Neil Heather, Univ. Queensland, and an anonymous reviewer are thanked for reviewing this manuscript. USDA is an equal opportunity provider and employer. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA.

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