Abstract

Food irradiation is an emerging technology for the 21st century. Extensive research and development worldwide in the past 40 years have proved the versatility and efficacy. With low, medium to high dose, and using either a gamma, electrons, or x-ray source, radiation can: 1) disinfest plant products and spices; 2) extend shelf life of tubers, bulbs, and selected tropical fruits; 3) decontaminate meats and seafood; 4) sterilize spices and special meals; and 5) improve product utilization. Criteria for testing its efficacy include effectiveness, efficiency, and the ability to retain product quality. The use of irradiation as a quarantine treatment of tropical fruits is potentially attractive to countries growing these fruits. A two-prong research plan should aim at proving radiation’s effectiveness in preventing emergence of all insect pests that might be on a fruit, and determining that all quality attributes of a host fruit are retained after irradiation, subsequent storage and shipment. Commercial application involves conducting an economical feasibility study; market research and testing; selection of radiation source and irradiator type; training of personnel for plant operations, radiation safety and dosimetry monitoring; designing of packages and choosing the most cost-effective means of transporting treated fruits to market destinations. When all of these are achieved, it should lead to a continuous and profitable operation. Researchers at the University of Hawaii using a gamma irradiator from the mid-1960s to early 2000s had amassed a volume of data to prove the efficacy of radiation disinfestations. And installation of a commercial x-ray irradiator in 2000 on the Island of Hawaii has enabled fruit farmers and packers to use this technology for exporting tropical fruits to distant markets.

Keywords: Disinfestations, quarantine treatment, quality retention, commercial application, economical feasibility, market research and testing

1. Introduction

In the history of food preservation, technology such as canning, freezing, and microwave heating and their products took many years to be established in the food industry and accepted by consumers. Irradiation as a food preservation technology has been studied in various parts of the world for more than four decades. Acceptance and commercialization have been slow, somewhat similar to the controversial and slow development of pasteurization of liquid milk at the turn of the 20th century.

Several obstacles have caused the slow acceptance of food irradiation. Among these are negative images of nuclear power seen by the public toward the end of, and after, World War II. Using a radiation source to preserve foods carries a nuclear connotation and raises safety concerns. Many consumers are not adequately educated about the safety of irradiated foods. Investment for a commercial irradiator facility is high. As a result, it is very challenging for a food preserved with an unconventional technology to enter and compete in the market place.

Food irradiation has been described as a versatile, efficacious and safe process, but it has endured a great deal of controversy in years past. Compared to all other food preservation
technologies, irradiation can claim the highest level of versatility and efficacy. This technology can be shown as an emerging technology of the Twenty-First century.

2. Applications of Food Irradiation

Among all the food preservation technologies, irradiation is probably the most versatile. An irradiation process utilizes any one of three acceptable radiation sources that can: (1) inactivate insects such as fruit flies on papayas and mango seed-weevils in mango; (2) extend shelf life by delaying the ripening and senescence of some fruits, or by inhibiting the sprouting of tubers such as potatoes and onions; (3) decontaminate poultry, meats, seafood, and spices by killing harmful and spoilage-causing bacteria (for poultry, meat and seafood, refrigeration should follow irradiation); (4) sterilize by completely inactivating all microorganisms in meat products or prepared meals (This is mainly for space travelers and for patients with compromised immune systems); and (5) improvement of product utilization such as minimizing oligosaccharides in beans, and increasing fruit juice extraction. Table 1 summarizes these applications.

Table 1 Radiation Preservation of Various Food Products

<table>
<thead>
<tr>
<th>Application</th>
<th>Dose, kGy(^{(a)})</th>
<th>Example of Food</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insect disinfestations</td>
<td>0.15 – 0.50</td>
<td>Fruits, nuts, grain, dried foods</td>
</tr>
<tr>
<td>Sprout inhibition</td>
<td>0.02 – 0.15</td>
<td>Potato, onion, garlic</td>
</tr>
<tr>
<td>Delayed ripening</td>
<td>0.12 – 0.75</td>
<td>Banana, mango, papaya</td>
</tr>
<tr>
<td>Decontamination</td>
<td>3.00 – 30.0</td>
<td>Poultry, meat, spices, seasonings</td>
</tr>
<tr>
<td>Sterilization</td>
<td>45.0 – 56.0</td>
<td>Prepared meat and meals</td>
</tr>
<tr>
<td>Product improvement</td>
<td>3.00 – 40.0</td>
<td>Soy beans, dried vegetables</td>
</tr>
</tbody>
</table>

\(^{(a)}\) Unit of absorbed dose: 1 kiloray = 1 kGy = 100 krad = 1 kJ/kg

3. Insect Disinfestation

Fruits and vegetables are mainly carbohydrates, with pectin and sugars being the main components. The application of radiation disinfestation is in the range of less than 1 kGy. No adverse effects are expected. This is confirmed with a massive amount of experimental data observed in the aroma, flavor, texture and color of various tropical fruits plus numerous chemical analyses (Moy et al., 1999).

Insect disinfestation as a quarantine treatment of plant materials, also called phytosanitary measure, among those applications mentioned, is probably one of the most useful applications of irradiation. In tropical and subtropical regions, many species of insects invade fruits, vegetables, nuts, dried foods, and grains (Moy, 1985; Moy, 1986; Moy, 1989, Ahmed, 2001; Moy and Wong, 2002; Moy, 2004). To move fruits and vegetables from an infested area to a non-infested market, the produce must first be treated with an acceptable quarantine treatment procedure. Chemical fumigation with ethylene dibromide is no longer allowed or used in many countries. Heat and cold treatments can be used in some commodities, but the treatment regime is commodity-specific because of differing degrees of tolerance to heat and cold by a host material. Irradiation, on the other hand, can be applied to a group of fruits for controlling a number of species of fruits flies with a generic dose, such as 0.25 kGy, which is the minimum quarantine dose currently required by the U.S. Department of Agriculture (USDA) for fruits entering the contiguous United States continent from Hawaii or from foreign countries.
4. Sources For Food Irradiation

**Gamma Rays:**
For gamma ray sources, two radionuclides have been used in food irradiation: Cobalt-60 and Cesium-137. Co-60 is produced by neutron bombardment of Co-59 in a reactor. Ce-137 is a byproduct of separation processing of fission products. Co-60 has a half-life of 5.27 years, and produces gamma rays of 1.17 and 1.33 MeV (million electron volt). Cs-137 has a half-life of 30 years, and produces gamma rays of 0.66 MeV.

**Electron Beams:**
For electron beam sources, the linear accelerator has proved most useful. Energy level of up to 10 MeV can be used for commercial food irradiators.

**Converted x-rays:**
A third source of ionizing radiation for food application is converted x-rays. When electrons from a linear accelerator collide with a dense, heat-resistant plate, such as tungsten or a titanium alloy, x-rays are produced on the other side of the plate called Bremsstrahlung. The energy level is limited at 5 MeV. The conversion efficiency from electrons to x-rays is in the range of 5-12%, limited by the law of physics.

For many years, very few converted x-ray facilities for food irradiation were built in any part of the world. Scientists and engineers in the irradiation field felt that the low conversion efficiency was the main limiting factor. Gamma-radiation from Cobalt-60, with similarly good penetration as x-rays (wavelengths of the two sources overlap in the electromagnetic spectrum), is a proven technology through decades of research and commercial applications. Since 2000, however, several commercial x-ray facilities have been built in the United States, including one installed at Keeaum, the Island of Hawaii for irradiating tropical fruits as a quarantine treatment. Others that were installed in Minnesota, Iowa and elsewhere are for irradiating meat and poultry.

5. Types of Irradiators

Irradiators can be classified by purpose and size. Many small irradiators have been built around the world for research purpose. Most of these are Cobalt-60 gamma irradiators with initial loading of 30 to 50 kCi (kilocuries). Larger in size are pilot irradiators capable of conducting research, but mainly for irradiating large quantity of products for feeding tests, shipping studies, and commercial feasibility studies.

Commercial Co-60 irradiators with initial loading of 500 kCi to several million curies have been built around the world, mainly for sterilizing disposable medical supplies and some cosmetics. Most electron accelerators have also been installed for industrial uses, such as the cable and plastic industry. In recent years, a number of x-irradiators were built by converting electrons into x-rays to gain the deep penetration necessary for pallets of foods.

6. Criteria for Judging the Efficacy of Food Irradiation

Efficacy of a food process such as irradiation can be tested with three criteria: effectiveness, efficiency and retention of product quality. Irradiation is effective in inactivating undesirable insect pests and harmful bacteria. This has been proven with volumes of research in the past several decades (Moy, 1985; Molins, 2001). In terms of time required to complete the process in applications discussed above, irradiation is very efficient. Using irradiation as a quarantine treatment, for example, every carton of papayas moving on a conveyor would pass
through the radiation field in about 10 to 15 min. in a commercial irradiator. In comparison, the vapor heat treatment, another accepted quarantine treatment for papayas, requires more than four hr for the fruit’s center to reach 47.2°C (Moy, 1993).

The third criterion for efficacy test is product quality retention. All the quality attributes of a treated product must be retained when compared to those of the control, within a reasonable statistical confidence limit, e.g. \( p \leq 0.05 \) (Moy et al. 1999). These include chemical, nutrient, physical and sensory quality. An example to illustrate this point is some of the data on irradiated papayas conducted at the University of Hawaii from 1996 to 2002 (Moy et al., 2003).

7. A two-Prong Research Plan

Proving radiation’s effectiveness in insect control:

This area of research is for entomologists. Several concepts of using irradiation to control insect pests in foods can be considered: 1) killing the insect pests such as those in stored grains; 2) injuring the insect pests with radiation so that they lose the ability to fly or to crawl; 3) causing the insect pests to lose their ability to reproduce. The dose applied is usually near a minimum among the three concepts, but is sufficient to damage the DNA by cleaving at least one strand of the double helix. When the DNA’s in the insects’ eggs are damaged, they cannot advance to their normal full life stage and emerge.

Determining all quality attributes of an irradiated fruit are retained:

Quality attributes of a fruits consist of objective qualities and subjective qualities. Objective qualities include those that can be measured quantitatively, either by instruments or by chemical procedures. Main qualities to be measured are nutrients, chemical index, texture, and color. Subjective qualities are sensory qualities such as aroma, flavor, texture and color. These are measured by conducting taste panels of trained people who are familiar with the fruit being tested, and do not have a strong dislike for that fruit. (There are people who do not like papaya, and therefore should not participate in a taste panel of papaya).

Table 2 provides an example of testing and comparing quality attributes of a commercial cultivar of papaya between two irradiation treatments and a control.
Table 2 Qualities of papayas (cv. Rainbow) one week at 10°C after being irradiated at 0.75 kGy with an X-ray source and a gamma-source as compared to control fruits

<table>
<thead>
<tr>
<th>Quality (nutrient, chemical, physical)</th>
<th>Control</th>
<th>X-irradiated</th>
<th>Gamma-irradiated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitamin C, mg/100 g pulp</td>
<td>82.2 a</td>
<td>96.5 b</td>
<td>89.5 ab&lt;sup&gt;(a)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total Carotenoids, mg/100 g pulp</td>
<td>0.32 a</td>
<td>0.29 a</td>
<td>0.28 a</td>
</tr>
<tr>
<td>Total Soluble Solids, %</td>
<td>11.8 a</td>
<td>11.5 a</td>
<td>11.5 a</td>
</tr>
<tr>
<td>Titratable Acidity, % as citric</td>
<td>0.22 a</td>
<td>0.24 a</td>
<td>0.23 a</td>
</tr>
<tr>
<td>Texture, N/g (shear press)</td>
<td>0.85 a</td>
<td>0.72 a</td>
<td>0.99 a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quality (sensory: 7=intense; 4=moderate; 1=lacking)</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Aroma</td>
<td>4.2 a</td>
<td>3.7 a</td>
<td>3.8 a</td>
</tr>
<tr>
<td>Flavor</td>
<td>4.6 a</td>
<td>4.5 a</td>
<td>4.5 a</td>
</tr>
<tr>
<td>Texture</td>
<td>3.2 b</td>
<td>3.1 b</td>
<td>4.1 a</td>
</tr>
<tr>
<td>Color</td>
<td>5.9 ab</td>
<td>5.7 b</td>
<td>6.2 a</td>
</tr>
</tbody>
</table>

<sup>(a)</sup>Means are triplicate analyses of three experimental runs. Triplicate runs in each of three experiments with 20 panelists participating in the sensory panels of multiple comparison test on alternate days. Different letters across each row of data indicate significant difference at p<0.05.

These data show that with minor exceptions (Vitamin C and sample color by sensory evaluation), most of the qualities of irradiated papayas are comparable to those of controls. The conclusion was that the quality of irradiated papayas of the Rainbow cultivar was well retained. Considerable amount of experimental data supports this conclusion.

To sum up the above, foods such as fruits and vegetables will be irradiated under 1 kGy. The tolerance dose of these commodities should be studied and determined individually. The tolerance dose is preferably three times the minimum quarantine dose because of the possibility of a high maximum/minimum dose rate ratio in a particular commercial irradiator.

8. Government Regulations on Irradiated Foods

More than 40 countries around the world have approved more than 50 foods or food groups for commercial irradiation for various purposes and marketing. Up to the present, each country has its own regulations, established by its national health authorities. Some of these regulations follow national legislation. For example, in 1958, the U.S. Congress in the Food Additive Amendment to the Food, Drug and Cosmetics Act, defined sources for food irradiation as an additive. Subsequent regulations proposed and finalized by FDA on food irradiation have followed this definition.

Health authorities of other countries established regulations on food irradiation mostly on a case-by-case basis. A Joint FAO/IAEA/WHO Expert Committee on the Wholesomeness of Irradiated Food (JECFI) provided facts, conclusions, and recommendations which many countries have used as reference for their regulations. Each country also reviewed available safety data and considered advantages of irradiating a certain food or food groups for the national markets. As a result, the food items and the purposes for irradiation vary from country to country. However, the approved list of foods cover all the applications mentioned except product improvement.
Readers can visit the website www.iaea.org/icgfi and look for the database on clearance of irradiated foods in various countries.

The acceptance of the concept of ‘chemiclearance’ by the U.S. FDA to approve irradiation of food groups such as fruits or meat was a milestone in rule-making for irradiated foods. In April, 1986, FDA allowed irradiation of fresh foods up to a dose of 1.0 kGy for purposes of disinfestation and delaying maturation. The concept of ‘chemiclearance’ is that if food ‘A’ has been tested by chemical analyses and feeding studies, and found and judged safe for commercial irradiation, and food ‘B’ has similar characteristics and chemical properties as food ‘A,’ then food ‘B’ can be cleared for irradiation without having to be subjected to all the chemical analyses and feeding studies (Diehl, 1995). As a result of the clearance on fresh foods, all fruits are classified under one group, and approval is for the whole group.

In the U.S., all irradiated foods, except spices at the retail level, are required to be labeled, with a ‘radura’ logo, and phrasing such as ‘treated with radiation to control spoilage’ or ‘treated by irradiation for quarantine purpose.’ Manufacturers producing irradiated foods can identify the radiation source used, such as ‘treated with gamma-radiation,’ or treated with ‘ionizing radiation,’ or ‘treated with x-radiation.’ They can additionally add statements as part of a consumer education effort such as ‘this treatment does not induce radioactivity’ as long as the statements are truthful and not misleading to the consumers.


The economics of food irradiation is dependent on several parameters: (1) applied dose, which is related to purpose and application; (2) packing densities, which influence structural design and radiation physics; (3) throughput, which determines how often the irradiator is used; (4) dose uniformity, which is related to tolerance dose (the upper dose for a specific food), the maximum dose (by government regulations) and minimum dose (for quarantine treatment purpose).

Whether it is gamma irradiator or a machine irradiator (electron or X-rays), an economic feasibility study should be carried out for a planned irradiator. The study involves the following steps: (1) developing a model; (2) defining product type and describing the process; (3) making some necessary assumptions, (4) deciding on the type of irradiator, (5) defining the annual throughput, (6) calculating total processing cost and unit processing cost. When the unit processing cost is competitive with other processing costs, and the irradiated product can have a share of the market, then the use of irradiation can be considered economically feasible.

Processing cost is a combination of capital cost and operating cost, or fixed cost and variable cost. Capital costs of a free standing irradiation facility include the cost of hardware (irradiator, totes or carriers, conveyors, control systems, and ancillary equipment), Co-60 or accelerator, land, shielding, warehouse and laboratories. Operating costs include salaries, utilities, packaging, maintenance, taxes and insurance, interest on the loan, supplies and chemicals, transport, source replacement, and return on equity.

A number of well written cost analyses of food irradiation are available in the literature, such as those by Urbain (1986) and Kunstadt (2001).

Up until now, foods irradiated in each country are sold within that country. There has been no bilateral or international agreement or policy on trade of irradiated foods. But this may change in the near future with free trade agreements among several countries, e.g., the North America Free Trade Agreement between the U.S.A., Canada and Mexico, and among many countries under WTO (World Trade Organization). Also, within the past few years, USDA-APHIS has developed policies and implemented new regulations allowing foreign countries to
export certain fruits and vegetables into the United States after they are properly irradiated as a quarantine treatment (Anon., 2001).

10. The Prospect of Food Irradiation

In the more than four decades of research and development in food irradiation, people in the 21st Century will witness more applications of radiation as an emerging food preservation technology. Government authorities, the food industry, and researchers need to work together to provide more consumer education about the purposes, benefits, and safety of food irradiation. The general public will slowly accept this technology as a sound and sensible technology.

The pace of adopting this technology by the meat and poultry industry will be slow, partly because of high investment in an irradiation facility, and partly because the industry tends to be conservative, and at the same time, tries to look for other less expensive ways of maintaining plant sanitation and minimizing contamination of all the products. On the other hand, growers and packers of tropical fruit, vegetable, and fresh herbs will be eager to explore new markets overseas since it has been proven that radiation is a very efficacious quarantine treatment of these products.

Hawaii can claim to be the first place in the world to use irradiation as a quarantine treatment of its tropical fruits such as papaya, mango, carambola, rambutan, litchi, longan, etc. Beginning in the mid-1960s, the Hawaii Research Irradiator was installed on the campus of the University of Hawaii. Research on using radiation to control several species of fruits flies was conducted by entomologists at the USDA research laboratories in Hawaii. Researchers at the College of Tropical Agriculture and Human Resources devoted their efforts in studying various aspects of using radiation technology as a quarantine treatment of tropical fruits. A major effort was in proving that most tropical fruits can tolerate radiation very well, and even with the dose rate variations of commercial irradiators, qualities of these tropical fruits were well retained. Commercial test marketing of irradiated Hawaiian tropical fruits began in 1995 until 2000. In 2000, a commercial x-ray irradiator was installed on the Island of Hawaii to treat large quantity of fruits for farmers and packers. This operation is continuing today.

11. Benefits of Food Irradiation

A major benefit of food irradiation to consumers is to improve public health by minimizing food-borne illnesses through decontaminating meat and poultry by irradiation. The Food Safety and Inspection Service (FSIS) of the USDA endorses the use of ionization as a technique for processing meat and poultry products to provide consumers with a safe, wholesome, and nutritious food supply (Derr, 1993). With more incidences of food-borne illness and 66 recalls of 30 million kg of contaminated beef, pork and poultry in the U.S. in 2002 alone, there is the impetus for the meat and poultry industry to make use of this technology for public safety and consumer benefits.

A large portion of our food supply, such as fruit, vegetables, grains, legumes, and dried foods, etc. are constantly invaded by many species of insect pests. By using radiation to disinfest these foods, our food losses can be minimized.

Also, by using irradiation as a quarantine treatment of fruits and vegetables, many of these products grown in fruit fly-infested areas can now be marketed in noninfested areas, thus increasing international trade.
References


