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Application of Irradiation Technology to Preserving and Improving Qualities of Agricultural Products

– Review –

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Abstract

Potential applications of irradiation technology in postharvest handling of agricultural products have been documented over the past five decades. The biological effects of ionizing radiation on food were demonstrated to have the potential both of reducing the storage losses by controlling spoilage microorganisms, insects, sprouting and ripening, and of improving the hygienic quality of raw and processed products. Food irradiation is recognized as a physical and cold process using gamma-rays from radioisotope sources and electron-beam from the accelerator. As one of the technologies or techniques for preserving and improving the safety of food, irradiation technology has been approved in some 40 countries for more than 200 individual items of foods and of these about 30 countries including Korea are commercially utilizing this technology. Although limited quantities of irradiated foods are available in the market now, the proper uses of this renewed technology will offer great possibilities not only for increasing the availability of postharvest agricultural products, thereby contributing to price stabilization in the off-season, but also for reducing reliance on chemicals used for sanitary and quarantine requirements. This paper deals with biological actions of ionizing radiation and its potential applications in the agri-food industry from the international point of view.

Key words: food irradiation, principles, application, commercialization

INTRODUCTION

Considering the ever-increasing food requirements in the world, the most practical way to increase availability of foods and foodstuffs is to minimize their postharvest losses. Losses reach to over 25%, which occur at any point in the marketing process, from initial harvest to final purchase and consumption by the consumer (1). Currently, two types of preserving and decontaminating methods for agricultural products, i.e., refrigeration and chemical preservatives or fumigants have been largely utilized in the food industry. However, the former has difficulties in both economic feasibility and controlling optimum-conditions depending on commodities, whereas some of the latter have been already restricted or prohibited to be used for foods and agricultural commodities in a number of countries mainly due to chemical residues, environmental pollution and potential health hazards (2-4).

The food industry is considerably interested in novel food processing technologies which promise to preserve and improve the quality of foods without heat or chemical additives and yet retain the food's inherent qualities. Irradiation is an emerging technology which is called a cold process and uses electromagnetic energy having the penetrating power (4). Food irradiation is recognized as an effective method for reducing postharvest food losses, ensuring hygienic quality of food and faciliating wider food trade (5,6).

The long history of researches and wholesomeness tests on irradiated foods concluded that "irradiation of any food commodities up to an overall average dose of 10 kGy presents no toxicological hazards and introduces no special nutritional or microbiological problems, hence toxicological testing of foods so treated is no longer required" (7,8). The approval by the U.S. Food and Drug Adminstration (9) of meat irradiation on December 2, 1997, has been universally hailed and ended a long chapter in the tumultuous history of an important technology for food safety and preservation. As of now, some 40 countries have approved this technology for treating various food items; of them approximately 30 countries are using food irradiation technology for commercial purposes (10,11).

In this review, fundamental aspects and potential applications of irradiation technology are dicussed. The recent developments in the fields of food irradiation are also addressed associated with its practical implementation.

IONIZING RADIATION AND ITS BIOLOGICAL ACTION

Food is routinely processed with different wavelengths of radiant or electromagnetic energy. These include infrared waves used in traditional baking and broiling, microwaves used for quick cooking, and sunlight used for drying (6). They are part of the electromagnetic energy spectrum with ranges from the low-intensity broad waves of radio at one end to the very short high-intensity wavelengths of X rays and gamma rays at the other (Fig. 1). In a narrow sense, radiation sources cleared for food irradiation are gamma rays produced by the radioisotopes cobalt-60 or cesium-137, machine-generated X-rays with a maximum energy of 5 million electron bolts (MeV), and electrons with maximum energy of 10 MeV (7,8). The amount of radiation energy absorbed in target food is measured in units of gray (or kilogray, kGy). One gray equals one joule per kilogram.

Gamma rays, X-rays, and accelerated electrons are known as ionizing radiations since they interact with molecules to form positively and negatively charged ions when they pass through food. These unstable particles decompose rapidly into highly reactive free radicals, which in turn react with each other and unchanged molecules (Fig. 2).

The effect of these reactions in the molecules of plant materials brings about several effects, such as the inhibition of sprouting/rooting and retardation of ripening. Large molecules such as deoxyribonucleic acid (DNA) are particularly susceptible to being broken into smaller molecules. This damage to the DNA prevents living cells from dividing, thus causing the sterility or death of contaminating organisms such as parasites, insects, larvae, bacteria, mold spores, and viruses. The more simple the organism, the higher is the radiation dose needed to kill it (Fig. 3, Table 1) (5,12).

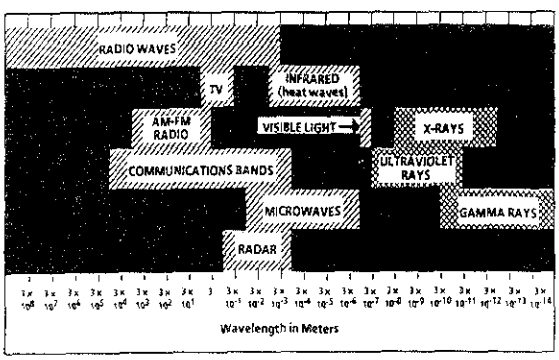

Fig. 1. Food irradiation with electromagnetic energy in broad sense.

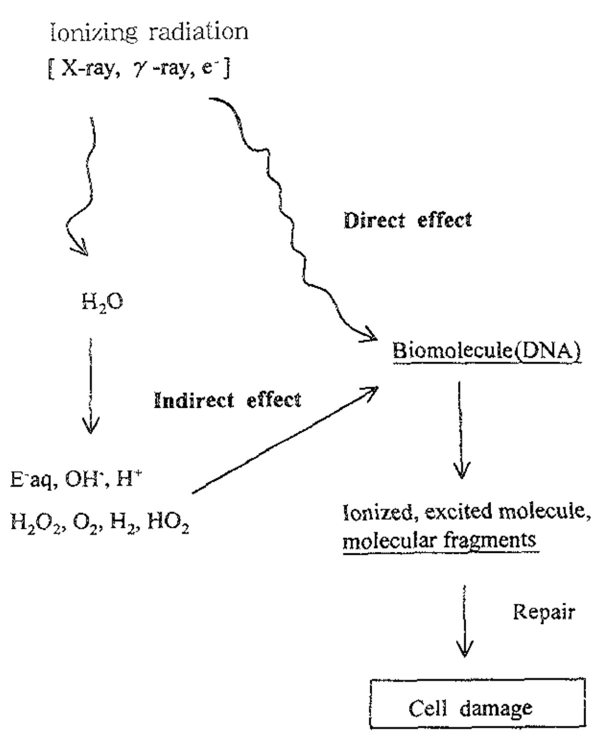

Fig. 2. Biological effects of ionizing radiations.

Basically, irradiation affects processes at the cellular level. For potatoes, onions and garlic, ionizing radiation interferes with cell division and thus prevents growth of sprouts during storage (13). For fresh fruit, ionizing radiation affects the ripening and aging processes, thereby keeping the quality and extending the shelf-life (4,14).

POTENTIAL APPLICATIONS OF IONIZING RADIATION

Various doses of ionizing radiation can be used for different purposes on preserving and improving the quality of food. Three dose ranges have been established for certain beneficial effects as shown in Table 2. Most uses of ionizing radiation on food, except for sterilization, require low to medium doses or less than 10 kGy. At this minimal level, irradiation at around 1 kGy inhibits sprouting in tuber and bulb crops and retards the ripening of fruits. It also acts as a disinfestating agent by sterilizing insects or killing their eggs and larvae (4,12, 15). The medium dose range, between 1 and 10 kGy, produces radiation pasteurization or radicidation. This level of treatment reduces the number of spoilage and disease-causing organisms. The process is thus useful for extending the shelf-life of some foods and reducing diseases carried by others. The highest dose range, usually above 10 kGy, produces radiation sterilization or radappertization. It is applied to aseptic diets or hermetically-sealed foods to reduce the microbial load to levels at which the product can be stored without refrigeration for several months.

This article mainly deals with domestic results on food irradiation researches using ionizing radiation that have been undertaken in Korea since the late 1960s (14).

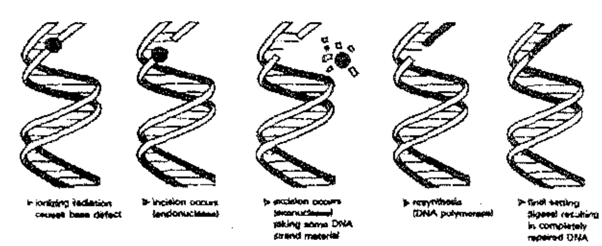

Fig. 3. DNA defect caused by ionizing radiation and its repair mechanism.

Table 1. Approximate doses to kill various organisms

Organisms	Doses (Gy)[1)]
High animals, including mammals	5 - 10
Insects	10 - 100
Non-sporulating bacteria	500 - 10,000
Sporulating bacteria	10,000 - 50,000
Viruses	10,000 - 200,000

[1)]To convert to rad, multiply by 100

Table 2. Dose requirements in various applications of food irradiation technology

Purpose of treatment	*Dose (kGy)*[1]	Products
Low dose (up to 1 kGy)		
- Sprout inhibition	0.05~0.15	potatoes, onions, garlic, ginger, etc.
	0.25~0.30	chestnuts
- Insect disinfestation and parasite disinfection	0.15~0.50	cereals and pulses, fresh & dried fruits and vegetables, dried fish and meat, fresh pork, feedstuffs, etc.
- Delay of physiological ripening	0.50~1.00	fresh fruits and vegetables
Medium dose (1~10 kGy)		
- Shelf-life extension	1.0~3.0	strawberries, fresh fish, etc.
- Elimination of spoilage and pathogenic microorganisms	1.0~7.0	fresh & frozen seafood, raw & frozen poultry and meat, feedstuffs, etc
- *Improving physical properties of food*	2.0~7.0	*dehydrated pulses & vegetables (reduced cooking time), grapes* (increased juice yield)
- Decontamination	3.0~10.0	spices, herbs, poultry feeds, etc
High dose (above 10 kGy)		
- Commercial sterilization	10.0~	packaging materials, animal diets, enzymes, hospital diets, space foods, viruses, etc.

[1]Gy (gray): unit used to measure absorbed dose (100 rad, 1 joule/kg)

Sprout inhibition

Irradiation was used for the long-term inhibition of sprouting and preservation of the desirable qualities of tuber and bulb crops during storage. Potatoes should be irradiated within six to seven weeks after harvest to inhibit sprouting (16). Gamma irradiation at 0.15 kGy was enough for sprout inhibition for 9 months in a precocious variety and for more than one year in a late-ripening variety under the natural low temperature conditions (the year round; 2~17℃, 70~85 %RH), thus maintaining over 90% of marketability. Proper *curing resulted in the reduction of the rotting rate of irra*diated potatoes by healing the wounds in periderms. Irradiated potatoes were more stable in their physicochemical and organoleptic qualities than the nonirradiated control and were superior to control in their processing properties of potato chips (14,17).

The late-ripening varieties of onions and garlic were suitable for long-term storage by irradiation at 0.10~0.15 kGy, which should be done within one to two months after harvest. Drying of the outer surface and neck of the bulbs prior to irradiation is essential, together with proper controlling of relative humidities during storage (13,18,19). Sulfur-containing pungent components were resistant to irradiation at sprout-inhibition dose (Fig. 4) (20,21).

Irradiation could be utilized for sprout/or root inhibition of chestnuts. For both purposes, irradiation should be done as soon as possible after harvest. *A dose of 0.25 kGy was* required for the preservation of chestnuts for more than 7 months (22).

Shelf-life extension

Exposure to low doses of irradiation delays the ripening and/or senescence of some fruits and vegetables, thereby extending their shelf-life. Gamma irradiation at 1 to 3 kGy was applied to several fruits and vegetables (4,14), such as strawberry, peach, tomato, apple, pear, etc. Treatment effects on shelf-life extension were different according to the radiation tolerance of each commodity, and thus the feasibility of irradiation treatment is required to be studied from the practical point of view (Fig. 5). Shelf-life of fresh mushrooms was effectively prolonged by irradiation at 2 to 3 kGy (Fig. 6). A corrugated-paper box/polyethylene-*film wrapping* was proposed as a packaging method suitable for reducing quality deterioration. A combination treatment with mild heat or proper packaging methods may be successfully applied to some fresh fruits and vegetables (4,15,23).

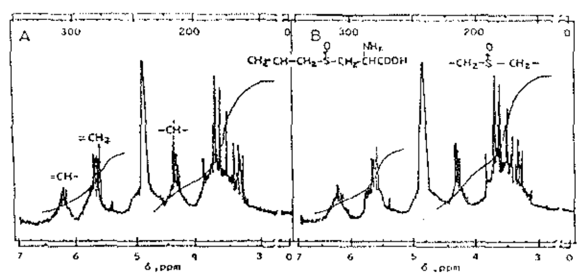

Fig. 4. Nuclear magnetic resonance spectra of alliin (S-allyl-L-cysteine sulpoxide) isolated from gamma-irradiated garlic bulbs (D_2O, 100 MHz, Varian HA-100). A: control, B: 0.15 kGy.

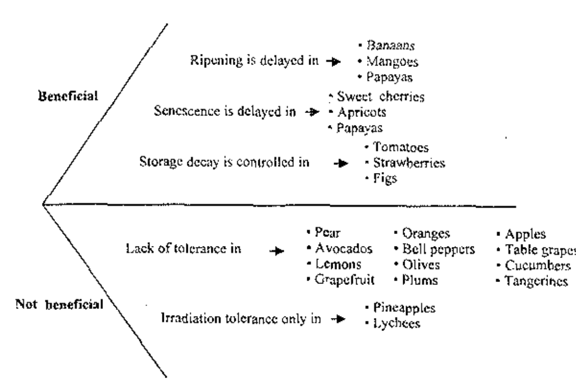

Fig. 5. The response of some fruits and vegetables to irradiation.

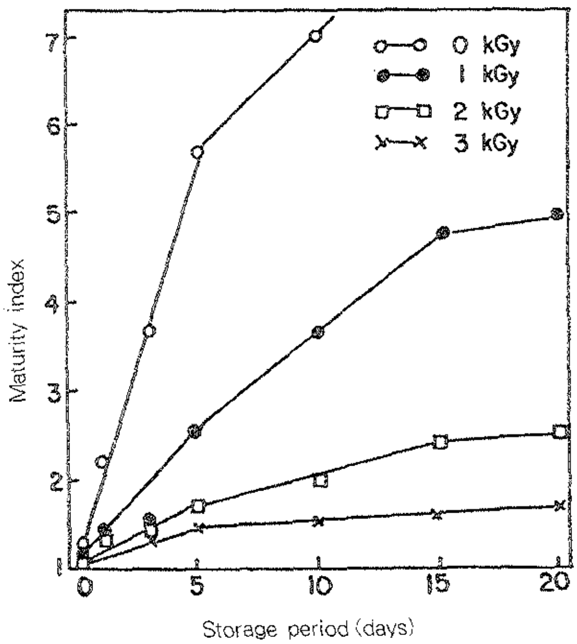

Fig. 6. Effect of gamma irradiation on maturity index of mushrooms (*Agaricus bisporus*) during storage at 9±1°C and 80±7%RH. Maturity index: 1, veil intact (tight); 2, veil intact (stretched); 3, veil partially broken (less than half); 4, veil partially broken (greater than half); 5, veil completely broken; 6, cap open (gills well exposed); 7, cap open (gills surface flat).

Disinfestation and microbial decontamination

A major application of food irradiation is to replace banned fumigants used to meet quarantine requirements. Because insect pests can cause major harvest losses, controls have been legislated around the world to prevent their migration (15). In addition, most countries have strict hygiene requirements for seasonings, spices, and herbs which are normally highly contaminated with microbes. To date the main process used to control microbes and pests in fresh and dried products has been fumigation with toxic gases. Methyl bromide which is the only broad spectrum fumigant used for agricultural products is anticipated to be restricted for future use due to its potential toxicity (24). As a result, nations exporting spices, herbs, and fresh produce have been anxiously seeking a suitable alternative to fumigation, one that preferably does not use heat (15). The application of heat to spices and herbs removes their characteristic flavor, and hot water dip used to disinfest fruits destroys their quality. Because food irradiation, as a cold process, can kill microbial contaminants and can sterilize or kill adult insect as well as larvae and eggs (Fig. 7), it is expected to be an alternative process to chemical fumigants of environmental interest (12,24,25).

In domestic studies (14), preestablished dose of 0.5 kGy effectively disinfested rice (Table 3) and barley during storage at room temperature for over one year.

Detectable changes in physicochemical and organoleptic qualities were observed in irradiated rice at more than 1 kGy. The development of packaging method for grains is required for increasing irradiation efficacy. Prepackaged-dried mushrooms were properly preserved by irradiation at 1 kGy for more than one year without insect attack (26). While powdered spices and condiments used in the food industry, such as red and black peppers, onions, garlic, ginger, mixed condiments, etc. were more effectively decontaminated by gamma irradiation at below 10 kGy rather than ethylene oxide (EO) fumigation, with minimal effects on the physicochemical and organoleptic qualities (14,27,28).

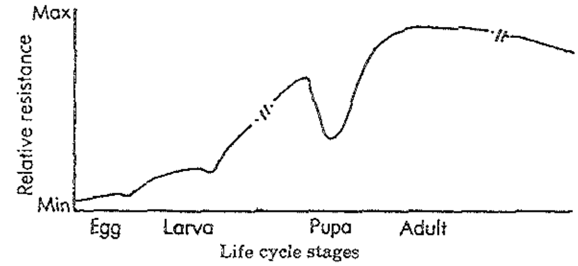

Fig. 7. Generalized pattern of resistance levels to lethal effects of ionizing radiation in insects.

Table 3. Adult's mortality and number of progeny delivered from irradiated adult of rice weevil (*Sitophilus oryzae*)

Dose (kGy)	No. of adults irradiated	No. of mortal adults	Percent of mortality	No. of progeny /pair
0	200	5	2.5	380
0.03	200	8	4.0	291
0.05	200	10	5.0	180
0.07	200	10	5.0	74
0.10	200	20	10.0	0
0.20	200	40	20.0	0
0.50	200	90	45.0	0
1.00	200	200	100	0

Improvement of physical properties

In water absorption or rehydration of dried soybeans and mushrooms, the time required for equilibrium moisture content reduced according to increase of irradiation dose. Irradiation also caused the considerable reduction in their soaking and cooking time (29).

Safety and wholesomeness of irradiated food

Since irradiation was evaluated as a physical process as early as 1976 by FAO/IAEA/WHO Expert Committee, another conclusion was led in 1980 that "irradiation of any food commodities up to 10 kGy causes no toxicological hazards, along with no special problems in the nutritional and microbiological aspects" (7). The microbiological safety of irradiated food was further reaffirmed by the Board of the International Union of Microbiological Society in 1982. The Joint FAO/WHO Codex Alimentarius Commission (CAC) was satisfied regarding the above evaluations and adopted "the Codex General Standard for Irradiated Food and the Recommended International Code of Practice for the Operation of Radiation Facilities for the Treatment of Food" in 1983 with recommendation of them for acceptance of all its member countries (8). In the latest assessment on the safety of irradiated food, WHO concluded in 1992 that under existing good manufacturing practices the irradiation process will not introduce changes in the composition of food which can produce adverse effects on human health, nor can it increase microbial risks to consumers (30). With increasing interest in using irradiation processing to sterilize various food products to provide them with shelf-stability for specific populations (hospital diets, immuno-compromised persons, armed forces, etc) and to increase the availability and variety of shelf-stable foods for the general public, FAO/IAEA/WHO convened a Joint Study Group on the Wholesomeness of Food Irradiated with Doses above 10 kGy in Geneva, Switzerland, 15~20 September 1997. After considering data on toxicological, nutritional, microbiological and radiation chemistry aspects of food irradiated with doses above 10 kGy, the Joint Study Group concluded that food irradiated under proper conditions appropriate to the intended technological aim, is safe for consumption and adequate for nutrition. Therefore food irradiation is considered to be wholesome for all technological doses either below or above 10 kGy (11,30).

Advantages and disadvantages of the technology

Food irradiation involves exposing foodstuffs, either prepackaged or in bulk, to carefully controlled amounts of ionizing radiation from approved radiation sources ; gamma rays from encapsuled ^{60}Co or ^{137}Cs sources, or electron beam or X-rays from electrical machines. Compared to any other physical processing, food irradiation has been thoroughly researched with respect to its safety and efficacy for treatment of food and is recommended for application by FAO, WHO and credible scientific bodies of many countries (7,8). One of the important advantages of food irradiation processing is that it is a cold and prepackaging process with lower energy consumption (31) and with negligible temperature rise in the food to be irradiated (only 2.4°C/10 kGy) (7). On the other hand, it was found that irradiation has some limitations in its use; off-flavors are induced in milk and dairy products resulting from irradiation, and by which lipid oxidation can be accelerated in fatty foods (4). The most important limitation of food irradiation is its slow acceptance by consumers, due *inter alia* to a perceived association with radioactivity. Additionally, lack of harmonization of regulations among the countries which have approved irradiated foods hampers the introduction of this technique for international trade, thus action at the international level has to be taken in order to remedy this situation (32).

Legistration and commercialization

At present, some 40 countries have approved irradiation of one or more food items for human consumption (10,11). The national regulations for food irradiation were enforced in September 1987 in Korea. Gamma radiation from ^{60}Co source is authorized to be used food irradiation of more than twenty items (groups) as given in Table 4.

Regulations prohibit reirradiation of food under any circumstances. The irradiated foods should be packaged before their sales using a proper container or appropriate materials. The regulations also require that prepackaged irradiated food be accompanied by the labelling with the international symbol for irradiated food (33).

More than 50 irradiation facilities including Shihoro Agricultural Cooperative Association ^{60}Co potato irradiator in Japan and Food Technology Service in the USA are being used for treating some foods in over 30 countries (11) (Fig. 8). Korea's first commercial food irradiator was established

Table 4. List of approved application of food irradiation in Korea

Item name	Type of clearance	Date of clearance	Dose (kGy) maximum
Chestnuts	unconditional	10/16/87	0.25
Mushrooms	unconditional	10/16/87	1.00
Mushrooms (dried)	unconditional	10/16/87	1.00
Onions	unconditional	10/16/87	0.15
Potato	unconditional	10/16/87	0.15
Spices	unconditional	9/13/88	10.00
Fish powder	unconditional	12/14/91	7.00
Garlic	unconditional	12/14/91	0.15
Meat (dried)	unconditional	12/14/91	7.00
Red pepper paste powder	unconditional	12/14/91	7.00
Shellfish powder	unconditional	12/14/91	7.00
Soy sauce powder	unconditional	12/14/91	7.00
Soybean paste powder	unconditional	12/14/91	7.00
Starch	unconditional	12/14/91	5.00
Enzyme preparations	unconditional	5/19/95	7.00
Sterile meals	unconditional	5/19/95	10.00
Vegetable seasonings (dried)	unconditional	5/19/95	10.00
Vegetables (dried)	unconditional	5/19/95	7.00
Yeast powder	unconditional	5/19/95	7.00

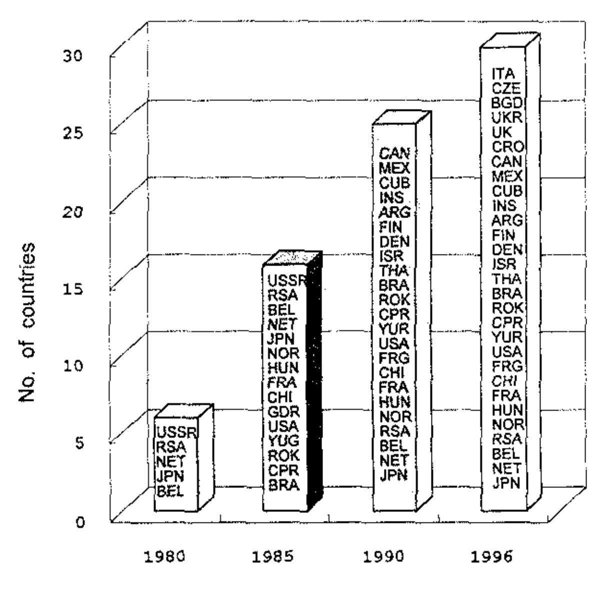

Fig. 8. Worldwide trend in commercial application of food irradiation.

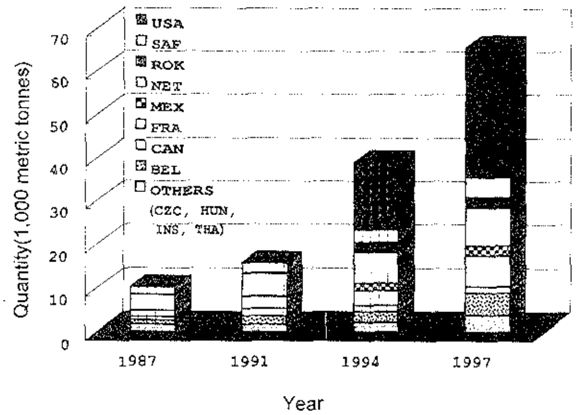

Fig. 9. Estimated quantities of irradiated spices and vegetable seasonings.

near Seoul by Greenpia Tech. Inc. in June 1987. From the beginning of its operation, it has been used for medical sterilization and food irradiation. Now, the operating rate of this irradiation facility has been gradually increased for treating different items.

In December 1991, a commercial food irradiation facility (Food Technology Service) was established in Florida, USA, which is presently irradiating strawberries, juice orange and grapefruits for commercial purposes (34,35). Even though the worldwide amount of irradiated foods (more than 600,000 metric tons per annum) is small in comparison to the total volume of processed foods and not many of irradiated products enter international commerce, the list of approvals and applications is growing as more countries are showing interest in the technology and more irradiation facilities are under construction (11) (Fig. 9). A typical example was the approval of meat irradiation by USFDA last year (9).

CONCLUSION

Following several decades of research, development and public debate, food irradiation technology is being recognized as one of essential technologies to feed the increasing world population, to protect consumer health from foodborne diseases, and to overcome barriers in food trade. This technolgy has potential applications, such as its practical use to ensure hygienic quality of solid food including spices and other dried food ingredients, as a quarantine measure of fresh agricultural produce, and as a disinfestation method for grain and other stored products. Although progress towards acceptance of food irradiation by the industry is slow, actual market trials have shown that once consumers have understood this technology, they are willing to buy and try irradiated foods. In this respect, further efforts are needed for continuous R & D from the technological and social points of view not only to educate the consumers with the factual information on the benefits and limitations of food irradiation in comparison with conventional methods, but also to enlarge the application fields of this technology. Considering the recent advances in food irradiation and restriction in the use of chemicals, there is every reason to believe that irradiation technology is expected to be practically utilized in the food industry.

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