FOOD PROCESSING WITH LINEAR ACCELERATORS

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The application of irradiation techniques to the preservation of foods is reviewed. The utility of the process for several important food groups is discussed in the light of work being done in a number of institutions. Recent findings in food chemistry are used to illustrate some of the potential advantages in using high power accelerators in food processing. Energy and dosage estimates are presented for several cases to illustrate the accelerator requirements and to shed light on the economics of the process.

The Problem

In many parts of the world, significant losses of food due to spoilage and insect infestation are a fact of life. It has been estimated that even in the United States, losses in certain crops may be as high as twenty percent. In poorer and less developed nations, the problem is even more severe. These nations lack sophisticated post-harvest food processing plants and in applying traditional techniques, the food is often exposed to a large variety of organisms. The situation is made even more serious by the fact that the climate is frequently quite conducive to spoilage, while packaging and storage methods employed are frequently inadequate. The benefits of reducing the losses due to spoilage may be viewed in the context of hunger in the developing nations or as an economic problem in the industrialized nations. For example, when one irradiates fresh seafood, the result is the destruction of microbiological organisms which cause deterioration and decay. In a developed nation, the increased shelflife increases the percentage of the catch which is actually sold and thus provides a benefit which is viewed as primarily economic. In a developing nation it directly affects malnutrition.

In addition to the problem of spoilage, there are significant difficulties associated with preventing the spread of insects from one region or country to another via host foods and commodities. The economics in this case are of great importance because the cost of eliminating or attempting to eliminate an exotic pest from a previously safe area is staggering. Effective quarantine treatment is thus a second important application of irradiation to the processing of foods and commodities.

The third principal use of radiation processing of foods is in the neutralization of dangerous bacteria or disease causing larvae. One of the most threatening bacterial disorders related to food processing is salmonella poisoning, resulting from the improper preparation of poultry, primarily chicken products. The bacteria commonly exists in the intestinal tract of the hosts and estimates of the number of cases annually are as high as two million in the United States alone. Parasitic larvae are responsible for the condition known as trichinosis. This disease is caused by the presence of Tricinella spiralis in the food chain of carnivorous animals. It is carried to man principally through the ingestion of pork that has been improperly cooked. Once the disease has been contracted, there is no known cure and medical treatment is limited to the relief of symptoms.

Irradiation - Experimental Results

Spoilage Control

A number of experimental studies have been conducted to determine the applicability of irradiation to food preservation. Khan et al [1] have examined the effect of varying radiation levels on several dried fruits. They studied apricots, dates, figs and raisins. They defined groups which were irradiated at doses of 0.25, 0.5, and 1.0 kGray, in addition to a control group. These samples were stored in polyethylene bags at room temperatures for a year and the samples were examined every two months in order to evaluate the extent of insect infestation. The results were similar for all four fruits, with no infestation manifested in any sample irradiated at the level of one kGy when examined after one year of storage. The authors evaluated the effect of the irradiation on color, total acidity, ascorbic acid content and sugar, finding no marked differences between irradiated and non-irradiated samples except in ascorbic acid content, which was significantly reduced in high dose samples. The fruits were subjected to a taste, texture and appearance evaluation and although the color darkened for all samples as storage time increased, there was universal agreement that the fruits which were subjected to the high dose were judged good after twelve months of storage, while those with no dose or low dose were judged to be poor.

In a study funded by the US Department of Energy, Johnson and Vail [12] studied the effects of several levels of irradiation on three diverse yet common fruit crop insects; namely, the Indianmeal moth, navel orangeworm and the driedfruit beetle in all developmental stages. They concluded that if dried fruits and nuts infested with these pests were irradiated at a dose level of 0.3 kGy the treatment would provide control comparable to processing with Methyl Bromide. A related effort by Fuller [13] was directed at the effects of irradiation on the quality of the almond, raisin and walnut crops. He irradiated the samples at a number of different dosage levels, up to 0.9 kGy. In order to simulate the effects of room temperature storage for long periods of time, he used storage at 98 degrees F. for shorter periods as an accelerated aging technique. He found that irradiation at 0.9 kGy did not cause immediate deterioriation in organoleptic quality of any of the products, but over time, the highest dose levels produced some indications of deterioration in quality and signs of rancidity in walnuts. He concluded that doses of 0.3 to 0.45 kGy would have minimal effects on the quality of the products even after storage.

Grain and cereal crops are of considerable interest in the study of systems for retarding spoilage. Bhuiya et al [9] investigated the use of ionizing radiation for the disinfestation of four varieties of pulses. They found that a dose of 0.32 kGy was sufficient to eliminate the beetles at all developmental stages. A very significant aspect of their work was their confirmation that the likelihood of reinfestation is very strongly related to the packaging materials used in storing the grain.

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Kovacs, Kiss and Kuroli [10] irradiated samples of wheat germ in order to eliminate various naturally occurring beetles whose presence limit the storage life of the product to one month. In addition to an evaluation of the effect of various doses of irradiation on the insects, they studied its effect on the taste and appearance of the product. They found that a treatment of 0.8 kGy effectively eliminated all developmental stages of the beetles and produced only minor changes in appearance, odor or flavor compared to untreated samples after both were stored for two months. They also reported a study of the use of irradiation to control weevils in wheat and found that a combination of heat treatment (40 degrees C for 30 minutes) and irradiation (0.45 kGy) produced the most effective result.

Copra and coffee are two crops of significant economic importance to the Philippines. Manoto et al [18] have found that the principal parasites of concern are the Copra Beetle and the Coffee Bean Weevil. They studied the effectiveness of irradiation in eliminating these pests from the crops to prevent losses during crop storage. They found that doses of 0.5 to 0.75 kGy were sufficient to control the Copra Beetle and doses of 1.0 to 1.5 kGy were effective in eliminating the Coffee Bean weevil.

Several Asian nations dry as much as fifty percent of their total harvest of fish. The traditional open air methods of drying employed offer insects an ideal opportunity to lay eggs on the fish. Loaharanu [4] refers to a number of workers from Asia who have studied the use of radiation in the disinfestation of dried fish. They have looked at a number of different species of insects and have found that a dose of 0.3 to 0.5 kGy is sufficient to control the larvae. They tested the organoleptic properties of the treated samples and found no decrease in quality.

Fish and seafood are important crops in the United States. The most likely application of radiation in the U.S. seafood industry involves increasing the shelf life of fresh fish, rather than reducing infestation in dried fish. Kaylor et al [5] studied the storage temperature history of fish from the Boston fishing fleet and found that 78% of the fish sent to market was fresh enough to justify irradiation. They also investigated the temperatures maintained during transportation and the transit times involved. They found that the times were short enough and the temperatures were low enough to assure high quality. Their analysis of the costs of the irradiation process led to the conclusion that it would cost approximately 5.7 cents per pound to irradiate to a level of 2 kGy, thus killing enough bacteria that the product would remain fresh in the retailer's case for about a week. The principal difficulty with the practical application of this study is that the levels of irradiation necessary to yield the shelf life improvement are twice as high as the present limit of 1 kGy set by the FDA.

Chicken can be considered a likely candidate for irradiation processing for shelflife improvement. Even with rapid processing and shipment, the shelf life of fresh poultry in the consumer's refrigerator is only four days or so. The use of irradiation to destroy bacteria which cause spoilage can be used to increase this time. In a recent report, Basker et al [7] used comparative taste tests to study the practical improvement in shelf life of chicken breasts and chicken legs. They found that at an irradiation level of about 3.7 kGy, the shelflife of fresh chicken legs is increased to at least 8 days, while it is increased to 21 days for breast meat.

Quarantine Disinfestation

Rigney and Wills [2] have studied the irradiation of fresh fruits for quarantine disinfestation. They included avacados, apples, tomatoes, nectarines, and grapes in their work and used a dosage level of 75 to 225 Grays. The lower value is sufficient to eliminate the Queensland fruit fly and the higher dosage was used to represent the assumed worst case max-to-min dosage of 3:1. Of all of the fruits studied, only the avocado was adversely affected by radiation. Avocados suffered vascular browning and a discoloration of the flesh even for doses of 75 Gy.

The quality of fresh fruits following irradiation was also studied by Moy and Nagai [3]. In response to the USDA-ARS recommended minimum absorbed dose of 0.26 kGy for protection against the Mediterranean fruit fly, the Oriental fruit fly, and the melon fly, they used doses of 0.25 kGy to 1.0 kGy. At doses of 0.3kGy, no detectable differences were noted in the quality of the irradiated fruit compared to the control group for plums and nectarines. Slight flavor differences were noted under the same conditions for peaches. California Valencia oranges were examined and found to be unaffected by a dose of 0.5 kGy if stored under refrigeration following irradiation. Papaya was found to be unchanged in quality following a dose of 1.0 kGy.

Disease Prevention

Another reason for the irradiation of chicken relates to the recent announcement by the USDA [6] that 37% of chickens purchased by consumers contain salmonella bacteria. In the same announcement, it was estimated that there were two million cases of salmonella poisoning in the US last year, most unreported. A study by a group in Canada [8] has concluded that 2.5 kGy is a sufficient dose to eliminate Salmonella in fresh or frozen poultry. Their taste and sensory evaluation showed that the panel could frequently distinguish between irradiated and non-irradiated but not as a flavor difference, rather by changes in texture and moisture. This led the researchers to conclude that the dose of 2.5 kGy would not have any significant effect on chicken in terms of flavor and chemical quality characteristics.

The parasite Trichinella spiralis occurs in pork and other mammals. Sivinski and Switzer [11] are developing a practical program for the elimination of Trininella in pork using a dose of only 0.3 kGy. They intend to demonstrate the logistical and economic feasibility of this process in eliminating the threat of trichinosis.

Summary

Since the irradiation levels required for the treatment of dried fruits and nuts for disinfestation produce no significant reduction in product quality, this seems to be an excellent application of irradiation technology as a replacement for chemical fumigation with Methyl Bromide or Hydrogen Phosphide. In an evaluation of the economics of the situation, however, Rhodes and Baritelle [19] point out that even with reasonably optimistic estimates of costs for irradiation facilities, irradiation is likely to cost five to ten times as much as current fumigation practice. The use of modified atmosphere processing, in which the product is placed in an artificially created nitrogen or reduced oxygen environment, is an alternative to irradiation and the authors point out that modified atmosphere processing is not only cheaper than irradiation, but is even cheaper than the product refrigeration required prior to irradiation.

The irradiation of cereals and grain is very effective in killing beetles and weevils but unless the product is packaged to prevent subsequent penetration by external pests, reinfestation occurs relatively quickly. Unfortunately, the packages which prevent entry of the pests also allow moisture buildup and this sometimes results in mildew, molds and product spoilage.

Irradiation as a solution to the problem of pest control in quarantine applications offers promise. There are significant crops of fruits grown in the Caribbean which cannot be sold or shipped to the southern regions of the United States because of the risk of transplantation of fruit flies and other pests.[14]

The problems posed by salmonella in poultry products and trichinosis in pork products are unique in that irradiation is capable of eliminating the threat while there may not be other practical solutions at this time. In a private communication [15], the author has learned that some strains of the salmonella bacteria are becoming immune to common antibiotics. If this becomes a general trend, the effects of salmonella poisoning, particularly on the very young, very old or those weakened by another illness may be drastic and even life threatening. If this situation begins to develop, there will be considerable motivation to irradiate all poultry products and thereby eliminate the threat.

For these reasons, it would appear that the irradiation of poultry might be one of the first applications to develop on a broad front. The need is real, the dose required is low, the treatment is very efficacious and, as we shall show, the economics are realistic.

Food Chemistry

All of the irradiation mentioned above has been carried out using radio-isotopes at the relatively low dose rate which that process implies. Further, most of the foods studied were irradiated at room temperature. In most of the cases, dose uniformity is estimated, but acceptance of max/min dose ratios of 2.5 to 1 or even 3 to 1 is not uncommon. Just as the other classical food processing techniques might, when used in conjunction with irradiation, significantly modify the results, so also, the use of different dose rates, and dose uniformity, product temperature and atmosphere, can produce significantly different results in certain foods even when total dose is the same. Simic et al [16] present a comprehensive picture of the effects of irradiation on the chemistry of food. They attribute almost all side effects to the interaction of free radicals (produced by the radiation) with the molecules of the food product. They have found that the recombination of free radicals is encouraged by higher dose rates and that higher dose rates even suppress the interaction of free radicals with food molecules. They have also stated that irradiation of meats at low temperature (0 to -40 degrees C), produces a significantly higher quality result for the same applied dose, partially because the increased viscosity of the product reduces the mobility of the ubiquitous free radicals and therefore limits their opportunity to interact with food components. They also point to the importance of irradiating foods in a controlled atmosphere in order to reduce the available oxygen molecules. They note that use of evacuated pouches also eliminates oxygen which would be available for post-irradiation autoxidation which normally occurs. The presence of water also adds to the likelihood of free radicals and therefore relative hydration of the food is important.

In a discussion of the impact of total dose, Simic et al [16] point out that meats irradiated at room temperature with a dose of 10 kGy would have a higher level of radiolytic products than similar samples cooled to -50 degrees C and irradiated to a dose five times as high! This is a powerful argument for regulating the irradiation of foods through some more direct measure of their food chemistry rather than simply the total dose to which they have been exposed.

Practical Considerations

In comparing the use of accelerators to the use of radioactive isotopes for irradiation of foods, a number of factors must be considered. Cost, of course is always important and in this case, it is likely that it will not be the determining factor. Thus far, the estimates which we have seen show that the cost differences are small and go one way or the other depending on who is doing the estimate and on what assumptions are made. A second factor is the impact on the quality of the product itself and here, we must be cognizant of the arguments made by Simic et al [16] in favor of high dose rate processes and therefore in favor of accelerators. Further considerations of safety and public acceptance are both on the side of the accelerator solution. Limits on transportation of radioactive sources and ultimately, even on availability of replacement isotopes also combine to make the linear accelerator a more advantageous choice.

In order to evaluate the practicality of the useage of linear accelerators for food processing, we will consider the application which seemed most pressing based on the considerations above; namely, the irradiation of chicken parts to a dose of 2.5 kGy for the elimination of Salmonella bacteria. It is important to note that this example assumes a radiation dose in excess of the 1 kGy presently allowed by FDA regulations. We believe that the limit will be extended specifically for the processing of poultry. Assuming the use of the electrons directly, present regulations would permit an energy of 10 MeV. This beam would produce the best max/min dose ratio if used in a two pass process to irradiate both sides of tbe product. Cleland [17] has set out a formula relating maximum useful penetration depth to energy and product density. Using this, one finds that chicken parts packed to a depth of approximately three inches will be adequately irradiated in a two pass process by a 10 MeV electron beanm. Cleland also presents his formula for the beam power requirement as a function of absorbed dose, production rate and beam utilization efficiency. Assuming an absorbed dose of 3.75 kGy (to cover a 1.5 to 1 max/min dose ratio) and assuming a beam power of 10 kW, and a beam utilization efficiency of 50%, the production rate is found to be over 10,000 pounds per hour. We assume that the plant will operate two shifts and that the facility cost will be $2 Million with a ten year payoff (requiring $200k/year). We further assume power and maintenance costs of $50k/year, and labor costs of $150k/year. These yield a total operating cost of $200k/year and a capital depreciation cost of $200k/year for a total chargeable cost of $400k/year. The throughput is 10,000 pounds per hour for 4000 hours/year, yielding yearly production of 40 million pounds per year. This corresponds to a net added cost of chicken production of one cent per pound. This would probably add about five cents to the consumer's price per pound. If the Salmonella bacteria becomes a significantly more serious health problem, the additional cost of eliminating it at its source might be considerably less than the health care costs associated with treating the disease.

Conclusion

There are a number of important potential applications for the irradiation of food products. Several of these were discussed and the experimental results of a number of authors presented. In terms of system design, we have found significant advantages of accelerators over radioactive isotopes in the processing of food products, not the least of which is a higher level of organoleptic quality. We have postulated that the existence of a real need and an economical solution to that need in the form of irradiation will motivate the proliferation of the technology in the real world. We suggest that the processing of chicken and pork to prevent disease might represent such a real and pressing need. A crude cost model of a system designed to irradiate chicken parts in order to eliminate Salmonella bacteria shows the cost to be about one cent per pound.

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