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Research priorities relating to food irradiation

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Introduction

Never before in the history of food preservation has so much effort been expanded on the research and development of a food preservation method as the irradiation of foods. Considerable financial support has been given to major research centers and laboratories all over the world in order to evaluate the technological and economic feasibilities of the process. Concurrent with these activities food toxicologists, nutritionists and chemists have evaluated the wholesomeness of irradiated foodstuffs. However, commercial applications of food irradiation have been rather limited compared to the more traditional methods of preservation such as thermal processing or chemical preservation.

The objectives of this study are to summarize the actual state of art research activity with special consideration of the studies since 1985, to indicate the problems and the remaining knowledge gaps and to suggest avenues to overcome them.

1 State of the Art

1.1 The food irradiation treatment

Next to the actual state of the art of food irradiation process brief general definitions about irradiation are given.

Food irradiation is one way of food preservation. The process involves exposing a food product to a source of ionizing radiation.
The major sources of ionizing radiation are radioactive isotopes such as Cobalt 60 and Cesium 137 which emit gamma rays, and electrochemical devices, which produce x-rays or beams of accelerated electrons. Gamma rays and x-rays are electromagnetic radiation of the same nature as normal light or microwaves but with greater energy and much shorter wave lengths.

Irradiation processes have been used already for some 20 years for the sterilisation of disposable medical supplies, pharmaceuticals that are ingested or injected, and products such as sutures or implants which remain in the body. 30% of these products are presently sterilized by irradiation in about 150 plants and commercially used all over the world (Kooij).

Units of measure

To characterize and measure the intensity of radiation energy following units are used:

a To characterize the radiation:

- eV: Energy of radiation is measured in electron volt (eV). Cobalt 60 emits Gamma rays of 1.3 MeV.
- Bq: Bequerel is the number of radioactive degradations per second, generating α, β,or γ radiation.
- Ci: Curie is a unit used for active preparations (1Ci = 3.7 x 1010 Bq).

b To characterize the amount of absorbed radiation energy:

- Gy: Gray is the unit of energy absorbed from radiation (1Gy= 1J/kg).

1.1.1 The irradiation process

The irradiation process comprises two main features, the radiation source and the facilities necessary to expose food to the radiation source.

The most common type of radiation source is typified by the radioactive cobalt sources, normally designated Cobalt-60 or Cesium-137, packed into stainless steel tubes as granules or pellets. In practice generally Cobalt-60 is used, because Cesium-137 has a number of drawbacks (low penetration depth, additional beta radiation, and heat production). While emitting gamma rays, the intensity of the source diminishes. As a result, the source is renewed periodically (the yearly loss of activity of Co-60 is about 12%), and the gradual changes in intensity is corrected by adjusting the exposure times. This decline is independent of whether material is treated or not.

Electron accelerators use electric and magnetic fields to produce a stream of high velocity electrons with negative electric charge.

The upper limit is generally fixed at 10 MeV for energy emerged by gamma rays and at 5 MeV for electron and x-rays, to exclude the problem of induction of radioactivity while radiating food. The threshold energy of the main components of food is 13 MeV or more.

In practice it depends on the case of application whether a radiation source or a electron accelerator is more appropriate.

A gamma ray source

* is characterised by a good penetration power. Therefore it will be used if food in larger packaging units is radiated.

* has a high reliability, because defects will only be of mechanical kind and can be repaired by ordinary trained staff.

Electron accelerator

* Unlike gamma rays electrons have relatively limited penetrating power. While larger containers with food can be radiated with gamma rays, the penetration depth of electron rays is limited to 5-8 cm (density 1).

* The dose rate is very high, therefore it allows a high throughput (e.g. irradiation of grain),

* the dose can be varied for every kind of packaging unit,

* in addition, the machines can be switched off,

* in smaller units the equipment can be integrated into the production line,

* the use of an accelerator requires a specially trained staff and is much more sensitive to breakdowns than a gamma ray source.

* in spite of that it is predicted that electron accelerators will be used more and more in future, because there is a lack of radioactive material and the public pressure by the use of accelerators is far less than by the use of radioactive materials.

The expenses of both processes depend on different factors (local electricity charges for accelerators, costs of Cobalt-60 for a Gamma rays source).

X-rays, used in medicine and industry for decades, may be a good compromise between penetration depths and investment required but the operation costs are very high. Cost-effectiveness remains to be demonstrated by a new type of x-ray generator (Campbell).

Irradiation facilities

The central feature is the source within the radiation room. Sources made of cobald rods are continuous emitters of radiation and they cannot be switched off unlike electron generators. When not used they are lowered into an energy absorbing medium, usually into a water filled pool under the radiation room. The unit itself is screened by thick concrete to prevent worker and environment exposure to the source.

The different types of gamma ray sources differ mainly through their conveyer systems. To radiate food, food is passed through the room on either a conveyor belt or a monorail system. Normally the food is fully packaged before entering the room. Monotoring of exposure time is carried out by dosimetric testing.

Some plants are equipped with a system to expose pallet loads to the gamma energy source and control the exposure time for each pallet and product type via computer. Gammaster in the Netherlands, for example, is a commercial operator of such a sophisticated system.

The **efficiency** of the use of the radiation source is 30%. An important point of efficient treatment is the establishment of the correct exposure time, which depends on the intensity of the source on the one hand and a number of conditions on the other:

* the minimum absorbed energy to fulfill the objective of the treatment;
* the allowable ratio between the maximum and minimum doses;
* the dimensions of material during treatment;
* the absorption rate of the material;
* one or two-side treatments;
* the energy density distribution within the system.

The ratio of maximum absorbed energy: minimum absorbed energy is important for a correct treatment. A value of 1.5-1.6 is achievable in modern systems (Berg).

Dose of radiation

The effect of radiation depends on the amount of radiation absorbed by the material. The dose is defined as the radiation energy absorbed in a volume, divided by the mass in this volume. The energy is measured in Joule, the dose in J/kg, or Gray in the SI-system.
1J/kg = 1 Gy; 1000 J/kg = 1 kGy

For the irradiation of food three terms are used to describe the range of effects:

1. *Radappertisation*. Dose rates in the range of 20-30 kGy sufficient to sterilise the food completely. Food treated in this way can be stored and treated just like canned food.
2. *Radurisation*. This covers medium range applications in the range of 1-10 kGy. It is targeted upon the reduction of microbiological load and the elimination of specific pathogens. The term implies pasteurisation by irradiation.
3. *Racidation*. Dose rates below 1 kGy aimed at extending fresh life and preservation of sprouting.

1.1.2 Dosimetry

The control and measurement of adsorbed radiation dose received by a food product is of paramount importance to assure the quality of the irradiated product and to assure regulatory compliance. Dosimetry is the only independent method that can guarantee the quality and reliability of the process. Dosimetry thus forms the basis for documentation, fulfilling the legal, regulatory and technological requirements of the food irradiation process.
In general, regulatory authorities require the food processor to control the irradiation process so that all parts of the food product receive an absorbed dose within certain prescribed limits.
The variation in absorbed dose with depth of absorbing material has important consequences for the uniformity with which any product can be irradiated. The dose distribution through a box, irradiated from two opposite sides can in a first approximation be represented by the sum of two exponential depth dose curves. Product of the end of the box will have received the highest dose D_{max}, whilst product in the centre will have received the least dose D_{min}. The ratio of maximum to minimum dose within a box, D_{max}/D_{min}, is generally known as the overdose ratio and its value will depend on the geometry of the irradiator and the dimensions and weight of the product box. For gamma irradiation often an approximation is made and the average dose is taken as $(D_{max} + D_{min})/2$. Typical values of overdose ratios are around 1.5 - 2, although values in excess of 3 may occur due to the inaccuracy of the approximation (Sharpe).

For measurements in electron beam accelerators the concept of overdose ratio is still valid although the relationship between D_{max}, D_{min} and $D_{average}$ is not straightforward, because each type of product container has to be individually "dose mapped" (Sharpe).

Adequate dosimetry with proper statistical controls and documentation is necessary to assure the food products are appropriately treated.
Therefore many current studies are engaged in the investigation about the dose distribution and the improvement of existing dose control systems for practical applications.

Radiation dosimeters are classified according to their rating by a standard hierarchy.
First there are the national standards, usually primary standards, held at the national standards laboratory. These primary standards are either ionisation chambers or calorimeters and measure adsorbed dose to carbon or metal with an uncertainty of $\pm$ 1 % or less.
Secondly are the reference dosimeters, divided in absolute dosimeters (Fricke, Ceric, Dichromate) and relative dosimeters (Alanine, Radiochromic films). Absolute dosimeters are systems whose radiation chemical response is characteristic of a particular solution composition. Relative dosimeters are systems which have to be calibrated against a standard. The overall uncertainty associated with reference dosimeters is about $\pm$ 3 % (Sharpe).

Routine dosimeters (see Table 1) are systems based on plastics, whose performance is not as good as the reference systems, but whose ease of use and low cost makes them ideal for the day-to-day monitoring of radiation processes. Uncertainties associated with routine dosimeters are at best around the + 5 % level but environmental influence factors such as temperature and humidity can lead to large systematic errors (Sharpe).

Table 1. Typical routine dosimeters for food irradiation (Harwell Polymethyl Methacrylate (PMMA) Range) (Robin)

Designation	Dosimetry Range	Comments
Red 4024	5- 50 kGy	used for other radiation application
Amber 3042 Perspex	3- 30 kGy	developed specifically for food irradiation monitoring
Gammachrome YR	0.1- 3 kGy	covers low dose range, wide temperature range

An international task group was formed in 1984 within ASTM specially to develop standards for measuring radiation dose for food processing. The group has 78 members from 11 countries, representing the sections food industry, government, regulatory, manufacturing and university.

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1.2 The Need of Food Irradiation

All foods undergo compositional changes after harvesting, such as ripening in fruits, breakdown of the cellular or chemical structure by enzymes or bacteria or the production of toxins by bacteria. Unless food is consumed soon after harvesting, enzymic or microbial decay will occur with consequent loss of quality. On the global scale, around one quarter to one third of the world's harvest supply is lost as a result of too rapid ripening, growth in storage, insect infestation and bacterial or fungal attack. All food preservation techniques are used increasingly to prevent such losses and deteriorations during storage or trade.

Food preservation by irradiation differs from other conventional physical preservation methods by distinct advantages:

- Food irradiation is a low temperature treatment. In contrast to heat treatment food irradiation can be applied to foods in a frozen state or on other heat-sensitive foodstuffs (e.g., fruits).
- Food irradiation has a good penetrating power (gamma rays), which results in an unique way of treating foods of variable size (e.g., a whole chicken carcase or a sack of spices as well as prepacked foods) which eliminates the serious problem of cross-contamination during transport and handling.
- Food irradiation requires low energy, especially if compared to conventional methods of processing with heat or freezing.

The fields of application regarding the actual state of the art is shown in table 2.

Table 2. Applications of Food Irradiation (Diehl, Miester)

Effect of treatment	Radiation Dose (kGy)	Type of food
low dose (up to 1 kGy)		
Inhibition of sprouting	0.05-0.15	potatoes,onions,garlic, ginger-root etc.
Insect disinfestation and parasite disinfestation	0.15-0.50	cereals and pulses, fresh and dried fruits, dried fish and meat, fresh pork etc.
Delay of physiological process	0.50-1.0	fresh fruits and vegetables
medium dose (1-10 kGy)		
Extension of food shelf life by delaying mould growth	1.5-3.0	fresh fish,strawberries and some other fruits,vegetables and sliced bread
Decontamination of spoilage	2.0-5.0	fresh and frozen seafood, poultry and meat in raw or frozen state, eggs and egg powder etc.
Improvement of technological properties of food	2.0-7.0	grapes (increasing juice yield), dehydrated vegetables (reduced cooking time) etc.
high dose (10-50 kGy)		
Commercial sterilisation	30-50	meat, poultry, seafood (shellfish), some vegetables, baked foods, prepared foods, sterilized hospital diets
Decontamination of certain food additives and ingredients (Replacement of chemicals)	10-50	seasonings, spices, nuts, dried vegetables, enzyms preperations, natural gum, etc.

From the economic point of view the field of application with low or medium radiation doses are of main interest presently.

An **actual need** of radiation technology is seen in the field of application, where other alternative methods are either restricted, contested or not present.

*** Replacement of chemical treatment which may leave toxic residues**

Inhibition of sprouting

To prevent sprouting of potatoes which are to be stored for several months chemicals (e.g., IPC (isopropylphenylcarbamat) or CIPC (chlorisopropylphenylcarbomat)) are used to a large extent, but are forbidden in some countries such as Japan because of health reasons. Radiation technology is a suitable method to replace these chemicals.

Insect disinfestation

Large amounts of stored cereals spoil as a result of insect infestation. But increasing concern with the safety of certain chemical agents such as ethylene oxide used for decontamination and ethylene dibromide used as a fumigant for disinfestation of cereals and other dry products has motivated some western countries to restrict or ban their use. Inhibition of insects or other pests via irradiation is a powerful incentive to use it as an alternative to pesticides and disinfectants which can leave toxic residues.
It has been shown that doses around 1 kGy are effective at eliminating insects. But off-flavours (e.g., in rice) already can develop at low doses of 0,5 kGy.
The insect disinfestation is regarded to be very important for the third world and less for the western countries. For example, although the USA has allowed grain irradiation since 1963, there has been made little use of the process due to the prevalence of modified atmosphere storage.

Decontamination of foods

Spices and herbs are usually microbially contaminated to a big extent. The use of such spices in sensitive foods can not only lead to their rapid spoilage, but also result in a health risk for the consumer. Treatment with ethylene oxide was banned in several countries because of concerns about its carcenogenicity. Alternatives for the decontamination of spices, like alcohol vapour treatment or combination of protein coating and heat or others, do not show the expected success or quality or they are partially still in development. Spices are ideal candidates for irradiation, because their high intrinsic value allows the process costs to be offset more readily. In practice, irradiation doses of 8-10 kGy

reduce the microbial load to acceptable levels without adversely affecting colour or flavour in most cases (Farkas).
Decontamination of other dry ingredients such as herbs and enzyme preparations by radiation is a feasible alternative to fumigation with microbicidal gases. Radiation doses of 3-10 kGy have been proved to be sufficient to reduce the viable cell counts to a satisfactory level (Farkas).

Nitrite-treatment

A further potential use of irradiation is its ability to reduce the quantity of nitrite necessary in cured meats. This may become of practical significance if legislation further reduces the amount of nitrite permitted in these products.

The use of food irradiation for the replacement of chemical treatments strongly depends on the fact, to which extent the usually cheaper chemical conservation is licensed or accepted by the consumer.

*** Improvement of microbiological safety with minimal losses in nutritional quality**

Pathogenic bacteria

Of more importance is the fact from public health point of view, that ionizing radiation can be used to kill, or reduce significantly, the numbers of pathogenic bacteria (e.g., *Salmonella, Campylobacter, Vibrio, Listeria*) in a variety of other foods, such as poultry or fish.

Latest studies show that food borne disease caused by bacteria such as salmonella are a serious concern in developed as well as in developing countries. The frequency of Salmonellosis has increased almost explosively to be a public health problem world-wide. Several outbreaks of these diseases have been recorded in the past 5 years in Europe and North America. Such outbreaks tend to occur more frequently due to increasing use of prepacked convenience and fast food and a thoughtless handling by the consumer. It is the opinion of some scientific experts that the salmonella problem cannot be efficiently controlled without the use of food irradiation. Under various preventive methods (rearing procedures for poultry, decontamination methods and education of the public) one of the most effective measures is irradiation of poultry and poultry products (Kampelmacher). Methods like pasteurisation in frozen state are not possible.
In poultry, an irradiation dose of 2,5 kGy will effectively eliminate *Salmonella*. Increasing concern about *Salmonella* infection of poultry could therefore be dealt by irradiation.
General studies showed that for non-sporing bacteria doses of 3 to 5 kGy are sufficient to control potentially pathogenic bacteria in food (Farkas).

Parasites

Radiation processing at reasonable low doses, less than 1 kGy under specific conditions, appears feasible for control of food-borne parasites. Existing data promise significant reduction of risk of human infections by *Trichinella spiralis, Taenia solium* (Cysticercus cellulosae in pork), *Tania saginata* (Cyticercus bovis in beef), *Toxoplasma gondii* and *Opistherchis viverrini.* Published data indicate that these parasites are controlled by a dose of 0,15-0,6 kGy making infected food safe for human consumption (Farkas).

A special interest in irradiation of meat exists in many tropical developing countries, where food losses due to spoilage are extremely high and where the economic conditions for building up a freeze chain from the producer through the trade to the consumer do not exist.

Nevertheless it is pointed out by all experts that the process should never substitute the control of contamination by Good Manufacturing Practice (GMP).

*** Maintaining certain markets** particularly that of the United States which increasingly controls against Trichnosis (pork), salmonella (poultry) and insect pest (fruits). Beatle larvae inside mango fruits, for example, cannot be reached by gas treatment. Therefore import of mango fruits from Hawaii to continental USA is forbidden. Only irradiation could open this ready market to the producers of mangos.

*** Improvement of quality and availability to tropical fruit products** hitherto not available because of insect infestation and poor shelf life. Detailed studies of treatment of fruits showed that shelf life can be extended if sprouting and ripening can be inhibited in certain fruits and vegetables with the use of irradiation, but in practice there is a number of severe limitations in its application. Fruits retain their raw state.

The examined effects of irradiation to date on the delayed ripening of fruits and vegetables are summarized in table 3.

Table 3. Irradiation response in fruits and vegetables (Loveridge)

desired technical effect	commodity	phenomena limiting commercial application
1. Delayed Ripening	bananas mangoes papayas	cheaper,more effective alternatives
2. Delayed Ageing	sweet cherries apricots tomatoes	tissue softening
3. Increased Storage Time	strawberries figs pears	abnormal ripening, cheaper and more effective alternatives
4. Irradiation Damage	avocados	cheaper, more effective alternatives
	nectarines	browning and softening tissues
	lemons	tissue softening cheaper and more effective alternatives
	peaches	tissue softening
5. Accelerated Ripening	grapefruits pineapples	
6. No positive effect	apples plums grapes	cheaper, more effective alternatives, tissue softening

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1.3 Effects of irradiation on food

No other conservation process has been studied so accurately with respect to risks for the consumer in the past years (Grünewald, Delincee). In various publications major findings in the wholesomeness studies on irradiated foods are reviewed. Mostly these examinations were done before 1980. Essentially investigations

- of harmful chemical degradation or additives (radiation chemistry, toxicology, microbiology),
- of the influence on the nutritional excellence
- of the effects on the natural taste and texture

were made.

The international competent expert committee of the World Health Organisation for the judgement of irradiated food, the International Atomic Energy Association (IAEA) and the World Health Organisation (WHO) came to the conclusion from analyzing of the results of 1980 that food treated with radiation doses up to 10 kGy is toxicologically unobjectionable and it is not related to any microbiological or nutritional problems (WHO 1981).

In the following chapter the effects of irradiation on food regarding the actual state of the art are summarized.

1.3.1 Radiation chemistry

All foods, fresh or processed undergo degradation when exposed to heat, light or oxygen. Several degradation products are known to be caused by thermal denaturation and oxidation.
The first step in degradation is the formation of "free radicals". Free radicals have short life and occur usually in all foods. The degradation products formed when a food is exposed to ionizing radiation are called radiolytic products. Products of radiolysis are present in very small quantities (ppm-range) and do not persist in food in presently measurable amounts. The major food components - of water, protein, lipids (fatty materials) and carbohydrates (starches, sugar and cellulose) - are vulnerable to radiolytic attack. Fats are the most vulnerable to free-radical disruption and oxidation. Mainly it seems that the identifiable products arise either from fragmentation of larger molecules, or in the combination of small fragments produced by the breakdown of smaller molecules. Some of the known radiolytic products are summarized in table 4.

Table 4: Common radiolytic products in main food components (Robin)

Food Component	Product
Protein	molecular weight peptide fragments no persistance of free radicals low molecular weight sulphur components
Carbohydrates:	
starches	glyceraldehyde dihydroxyacetone, malic, glycollic, formic acids
cellobiose	glucose
sugar	low molecular weight oxygenated compounds
Lipids (oils, fats)	low molecular weight hydrocarbons high molecular weight esters, carbon dioxide, hydrogen, carbon monoxide

There is a wide range of literature about kinds and extent of changes of the components of foods by irradiation (Elias and Cohen 1977, Robin). Regarding all present results the radiolytic products observed in irradiated foods are the same as the degradation products which occur in non-irradiated foods.

Continuous studies mainly deal with single changes in protein rich and fatty foods, of chemical and physical changes of carbohydrates, like starch or pectin and the effects of irradiation on enzymes.

1.3.2 Toxicological aspects

Though there are less changes caused by irradiation than by heat (baking, frying, cooking) it was examined whether unknown substances could be formed by irradiation which could be harmful to health after longterm consumption.

This was investigated by extensive and longterm animal-feeding experiments in several countries, but also by various in vitro experiments (e.g., mutagene effect in the Ames-assay).

For this purpose an international project (24 countries) was conducted from 1979 to 1982. A joint committee of experts of the World Health Organisation (WHO), the United Nations' Food and Agriculture Organisation (FAO), and the International Atom Energy Association (IAEA) concluded after considering all results that irradiation of food with low or medium doses (absorbed radiation up to 10 kGy) is generally unobjectionable for the health of the consumers. Regarding the mass of the present studies the committee declared explicitely that there is no need for further toxicological investigations for the range of doses up to 10 kGy. No statement was made about the range over 10 kGy because it was not investigated sufficiently.

The British government ordered to prove the study results again and the British expert team arrived in 1986 at the same results as the international team.

The US "Council for Agricultural Science and Technology" (CAST) published 1986 a report of a team of 24 experts about food irradiation being not injurious to health. This report confirms that food irradiation with doses up to 30 - 50 kGy is not injurious to health.

In the People's Republic of China experiments were carried out with volunteers for several months. 60 % of their food was irradiated and they did not show any negative effects.

Also no adverse nutritional problems have yet been recorded for patients consuming high dose (25 kGy) meals.

Currently some animal feed studies are continued in the USA (e.g., chicken) and in Asia.

However some authors say that the successful animal feeding trial cannot necessarily be translated directly to human consumers and there has been insufficient research to indicate whether subtle long term effects could occur from consumer exposure to irradiated foods.

Therefore in recent years, radiation chemistry has been recognized as an additional tool for toxicological evaluation, and the methods involved have been substantially refined.

1.3.3 Nutritional quality

Just as much as the above mentioned changes the influence of food irradiation on the nutritional quality has been investigated very intensively. In detail, the studies showed the following contents about effects on the nutritional quality in food through irradiation.

Numerous studies have confirmed that the biological value of the food protein is only negligibly impaired by irradiation even at a dose of high kGy. By breakage of peptide bonds and by reaction with free radicals the structural and functional (e.g.,enzymatic) properties of a protein can be inhibited. Nutrititional values of carbohydrates and essential fatty acids are not significantly affected, and minerals are unchanged in foods, which are radiated with doses admissible under these conditions. For carbohydrates, the most significant change is the disruption of the glycosidic bond that leads to a compromise of the structural integrity of food.

Polyunsaturated fatty acids are not reduced in chicken, filets of herring, rye and rice by irradiation. Only when rice was irradiated with a dose of 100 kGy a loss of 16 % of linoleic acid was found.

The radiation resistance of **vitamins** differs and it is a function of dose. Most of the vitamins, like vitamin B2, vitamin B12, niacin, folic acid, vitamin C, provitamin A, vitamin D, vitamin K do not suffer any significant losses from irradiation of admissible doses. Some vitamins, like the most radiation sensitive water soluble vitamin thiamin, suffer by irradiation. But these losses are not bigger than caused by other treatments (e.g., thermal processing). By modification of conditions of irradiation, in particular decreasing of temperature of radiation, the losses can be reduced considerably.
The losses of the most sensitive fat-soluble vitamin A and E can be reduced by excluding air during irradiation and storage.

Table 5: Influence of gamma rays and radiation temperature on losses of vitamin B1 in chicken meat (Diehl 1991)

dose of irradiation kGy	loss in comparison to unirradiated control objects radiation temperature 10°C	-15°C
0.5	0 %	0%
1.0	18.8%	11.2%
2.5	29.1%	22.4%
5.0	43.6%	28.0%
10.0	57.3%	44.8%

1.3.4 Microbiological aspects

Extensive literature supports the conclusion that radiation treatment at doses that do not cause unacceptable changes in organoleptic qualities can effectively eliminate potentially pathogenic bacteria from red meat, poultry and fishery products under normal commercial conditions for products which are marketed in both fresh and frozen state (Farkas).
Typical **radiation-sensitive bacteria** are those that commonly spoil meat and fish chill-stored in the presence of air (e.g., *Pseudomonas*), food-poisoning *Salmonella* bacteria that regulary occur in low numbers in some raw food materials.
Typically **resistent bacteria** are spore-forms of bacteria such as *Bacillus cereus* and non-sporing bacteria that have particulary highly effective DNA-repair systems (e.g. *Deinococcus radiodurans*).
Viruses are generally more resistant to radiation than most of many bacteria.

Newer research papers investigate the effect of irradiation on certain microorganisms like *Listeria monocytogenes.*

Another part of research deals with some particularly important safety questions, especially the production of toxins of bacteria and moulds:

* Could selective changes in the microflora, caused by non-sterilizing radiation dose, make known pathogens more likely to occur or bring into prominence unfamiliar pathogens? For example bacterial spores, such as *Clostridium botulinum*, if present, would survive and grow without competition when other organisms have been killed. They could produce toxins in food that appeared wholesome, owing to the absence of spoilage organisms (spoilage signal) that normally warn for spoiled food. Therefore food must be properly handled and stored after irradiation. Since spores are resistant to most forms of food treatment this problem does not differ fundamentally from other preservation procedures, but needs special attention for the post-irradiated handling of food.

* Could food poisoning be caused because ionising radiation effectively inactivates many microorganisms, with very little effect on the toxins that some of them have produced ? This potential problem is not unique to irradiation and is guarded against in the use of other preservation procedures as well.

New studies have shown, that there is no increase of the aflatoxin production rate only by irradiation treatment (Mitchell). Nevertheless, rules of Good Manufacturing Practice that are designed to prevent such occurrances,are necessary for food manufacturers.

* Is it probable that mutational (including adaptive) changes might make pathogens more virulent, more harmful or more difficult to recognize and could new pathogens arise in this way ?

Indeed, in the laboratory, irradiation is often used deliberately to obtain mutants, but these mutants are most often "crippled" (i.e., far less able to survive) and a number of practical studies over 30 years have confirmed that the induction of mutations in microorganisms has no significance in food irradiation (Egan). But most consumer organisations seem to dismiss perhaps too lightly the posibility that mutant pathogenic microorganisms might result from low levels of irradiation (Robin).

* Is it possible that development of radiation strains might render the antimicrobial irradiation processes ineffective?

The present literature of relevant scientific evidence related to these questions reaffirms the basic conclusions of earlier literature, that microbiological safety of irradiated food is fully comparable with that of foods preserved by other acceptable preservation methods. Similar to other preservation processes, gains in microbiological or keeping quality attained by food irradiation can be and must be safeguarded by proper control in the food irradiation facilities and by proper care of the product before and after processing.

Pathogenic organisms are generally more susceptible to irradiation than spoilage organisms, so food is generally made safer without necessarily being preserved.

1.3.5 Sensory properties

Off flavours

The effect of irradiation on the taste has been thoroughly investigated. The predominant part of research about sensory changes was carried out in earlier studies.

All foods and food ingredients will undergo flavour changes if exposed to a sufficiently high dose of irradiation but some foods are much more sensitive to this effect than others.
Changes in flavour on irradiation can arise from two main sources- initiation of rancidity development in lipids, and minor breakdown of proteins to give free sulphur-containing compounds. The combined effect of these two factors limits the maximum irradiation dose that can be applied to meat. Examples of quoted threshold doses are 1.5 kGy (turkey), 1.75 kGy (pork), 2.5 kGy (beef), 2.5 kGy (chicken), 3.5 kGy (rabbit) and 6.25 kGy (lamb). These doses are critically dependent on irradiation conditions and increasing irradiation temperature.
But low-fat foods (such as poultry meat, white fish, shrimps, prawns and spices) can be given amounts of radiation required to eliminate or significantly reduce the number of food-borne pathogenic bacteria before flavour changes develop which would make the product unacceptable to the consumer.
Fatty foods (e.g., fatty fishes) were unsuitable for irradiation because oxidation of fats leading to rancidity occured before the desired effect (e.g., the elimination of the food borne pathogens). The undesirable flavour is often described as "wet dog" or "metallic", but the development of radiation-induced flavours is not necessarily unpleasant; for example, irradiation of chicken can enhance the characteristic chicken flavour.

Fruits and vegetables are generally deficient in the proteins and lipids that give rise to deteriorate flavour changes in other foods. However, some flavour changes do occur. Some fruits can become sweeter, for example grapes, melons and cherries or can become less acidic and can change in characteristic flavour (e.g., strawberries). Flavour changes in vegetables are less easily defined, but include flavour loss in lettuce, production of bitter flavours in parsnips and musty flavours in celery. It must be noted, however, that the effects on many fruits and vegetables depend on a number of factors such as cultivation type, maturity and growing conditions.

Dairy products are generally more sensitive to off-flavours production than other foods, and acetaldehyde and dimethyl sulphide have been identified as radiolytic products. Off flavours are produced in milk at doses < 0.5 kGy through breakdown of protein and fat components. Cheese is slightly less sensitive to deterioration, and improvements have been observed in the flavour of ripe Camembert. Generally, however, changes are undesirable, such as the formation of smokey flavours in Cheddar cheese. Butter becomes rancid below 1 kGy.

Other foods that are subject to flavour changes on irradiation are eggs (off-flavour development in the yolk) and baked goods (rancid/metallic notes).

Texture

Textural changes can occur in meat by breakdown of collagenous material, producing an increase in tenderness. Breakage of peptide bonds by reaction with free radicals can inhibit the structural and functional (e.g., enzymatic) properties of a protein.

Some thickeners (e.g., carrageenans or starch products) loose viscosity. The most important textural changes, however, occur in fruits and vegetables by breakdown of carbohydrates. For carbohydrates, the most significant change is the disruption of the glycosidic bond that leads to the loss of the structural integrity of food.

The sensory quality of these foods is critically dependent on their textural characteristics, which in turn are determined by carbohydrate cell wall components and, in some products, starch granules. Degradation of carbohydrates such as cellulose, pectin and starch produces softening is generally (but not always) undesirable. Such degradation can weaken rigid structural tissues or alter cell walls to reduce turgor. In addition, changes to tissues can release endogenous enzymes to locations where they can attack carbohydrates, or changes to carbohydrates can make them more susceptible to enzyme attack.

The effect of irradiation depends not only on the type of product but also on cultivar type. Work on strawberries and raspberries has shown that, although some cultivars undergo unacceptable softening, others retain their firmness at doses up to 3 kGy. Grape skins loose their "bite" (although tough skins can become tenderized), apples can become softer and powdery and other fruits such as cherries and mangoes become softer. Vegetables such as peppers and Iceberg lettuce loose their characteristic crispness, although butterhead lettuces do not show significant changes. Cooking irradiated vegetables such as green beans produces a softening effect, which can be corrected by using shorter cooking times. At doses between 5 und 10 kGy, dried vegetables can be rehydrated more rapidly.

In addition to flavour changes, irradiation of egg products produces two effects: weakening of the membrane separating the yolk and white, resulting in leakage, and also loss in viscosity in the egg white.

Recent research investigates the changes of certain kinds of fruit and vegetables (e.g., strawberries or mushrooms). The benefits for mushroom growers are difficult to evaluate. Relatively little research has been conducted and the research has proven to be contradictory in terms of a prolonged shelf life.

Sensory aspects of mixed foods

The majority of published work has concentrated on assessing the microbiological and organoleptic effects of irradiating individual food items. There is consequently considerable information on the dose levels that can be used beneficially on individual items without incuring adverse organoleptic effects, but relatively little on mixed food systems in which individual items ideally require different optima between different components. In one investigation the effect of irradiation on the microbiological and organoleptic quality of a range of hot and cold meats was studied. This study demonstrated that a valuable effect could be achieved at low dose, but that further dose reductions would be desirable to avoid complex menu selection procedures (Kilcast).

Sensory aspects of combined treatment

In spite of the considerable research efforts concerning the irradiation of food, relatively little is known regarding the implications of organoleptic changes in food to the consumer. In considering the effects of combination treatments, it is important to assess both the reduced level of change resulting from lower irradiation doses and the effect of any additional treatment. This will be particularly important for combination of irradiation with heat treatments, and also combination of irradiation with some chemical treatment. For example, irradiation of mould in papayas requires doses of 2.5-6 kGy, which causes substantial damages of the fruit. Use of a 20 second hot water dip at 60 °C, however, reduces the necessary dose to 0.75 kGy. Under this combined treatment, it may be expected that the irradiation component would have minimal effect on organoleptic properties, whereas the heat treatment might produce some deterioration. Similarly, the 0.7 kGy dose needed to disinfect can be reduced to 0.035 kGy by air heating at 40°C.
At present known effects of combined treatments are summarized in the following chapter.

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1.4 Combined processes

Combination treatments have, as yet, been little used. But the major benefits of food irradiation will eventually be seen here, so is the opinions of experts.

In fact, such use of irradiation in combination with other treatments, may be the most effective way of using the process, as a number of reasons show. One is illustrated by the need to inactivate enzymes sometimes. Another results from the desirability of minimizing the effects on food flavour, which can sometimes be achieved by irradiating food in frozen state or by irradiating in the absence of oxygen, (in vacuum packs) or in a nitrogen atmosphere. A further reason is that irradiation not only inactivates microorganisms, but also has the effect of reducing the resistance of any survivors to some of the other preservation treatments that are already widely used. For example, bacteria subjected to a dose of irradiation that is insufficient to inactivate them, may nevertheless be made more sensitive to heat. Therefore most of the studies currently carried out are dealing with the effects on microorganisms.
Many of these benefits arise from synergetic reactions. Consequently, use of irradiation and heat together may allow foods to be preserved with less loss of quality due to heat-damage than with conventional thermal processing.

1.4.1 Heat treatment and irradiation

In some studies different types of microorganisms have different responses to the heat treatment/irradiation sequence. This is to be distinguished between the behaviour of fungi, where the sequence heat/irradiation has the higher anti-microbial efficiency. With resting spores, the sequence irradiation/heat is more effective.

Table 6. Example of successful heat/irradiation treatment schemes (Robin)

Comment	Food	treatment 1	treatment 2
extended shelf life	papayas(India/South Africa/Hawaii)	49°C/20 min/hot water	0.75 kGy
		50°C/5 min/hot water	1 kGy
	grapes (India)	dip	
delays *Aspergillus* rot	figs (India)	50°C/5min/hot water dip	1.5 kGy
delays ripening	bananas(India)	50°C/5 min/wet heat	0.25-0.35 kGy
reduces stem rot	bananas (India)	50°C/5 min/wet heat	0.25-0.35 kGy
	mangoes (India/ Australia)	50°C/5min/wet heat	0.5 kGy
control of fungal/ insect contact	mangoes (India)	5 min/hot water	0.75 kGy
	avocado(Chile)	45°C/5min/hot water PVC/shrink foil wrapping	0.25 kGy/
reduced spoilage	apple juice	70°C/8sec	3.5 kGy

Particularly noteworthy are the examples drawn from fruits which are normally radiation-sensitive, such as avocados. Table 6 only cites typical examples, but other foods treated successfully including tomatoes, lychees, melons, fruit juice concentrates, strawberry yoghurt, groundnuts (where the heat/irradiation combination inactivated toxigenic fungi as *Aspergillus flavus*, associated with the aflatoxin problem in groundnuts).
Overall, the combination of mild, moist heat and low dose irradiation seems to have considerable potential for delaying and reducing microbial, and particularly fungal, spoilage of many fruits and vegetables which are otherwise vulnerable or unsuitable to irradiation alone (Robin).

The above examples are based upon treatment of high water content food items with moist heat methods. A different situation exists when dry food ingredients are irradiated. Farkas (1990) has demonstrated, for example, that microorganisms which survive radiation treatment in spices become heat-sensitive and are more vulnerable to destruction in the heating of spice-containing foods than those in untreated or fumigated spices.

Bacillus or *Clostridium* spores become more sensitive (85% or 93%) by a combination of irradiation at a dose of 1-3 kGy, followed by heating 90°C/30 min (Wills).

A similar vulnerability to heat treatment has been demonstrated in insect pests associated with infestation. Temperatures of 40°C applied for the life cycle of the grain beetle and the warehouse moth following low dose irradiation significantly reduced their populations. It has been suggested that disinfestation could be made much more effective by combining low dose irradiation with microwave or dielectric heating. This would destroy pests selectively by greater absorbing power, leaving the grains relatively cool throughout the process and only exposing them to a limited dose (Robin).

The attractiveness of combining low dose irradiation with mild heating lies in their complementary effect upon bacteria and pests and their minimal effect upon the food itself. It seems certain that this combined process will develop much further and may allow the advantages of irradiation to be optimised.

But Farkas (1990) points out that combination treatments with irradiation - even the most promising ones - currently remain far from practical application.

1.4.2 Modified Atmosphere Packaging (MAP) and Irradiation

Nowadays, the application in MAP is in the packaging of cuts of meat both for wholesale and retail market. Carbon dioxide does not effect all bacteria equally. For example ***lactic acid bacteria***, such as ***lactobacillus*** (cause acidic sour spoilage) are less affected by elevated carbon levels than the major meat spoilage organisms (cause organo-sulphur based taints through spoilage) such as *Pseudomonas*. The attraction of combining irradiation with MAP is that the modified atmospheres are not lethal to spoilage organisms and pathogens. These conditions will only retard growth. The possibility exists, therefore, of using irradiation below the "threshold" dose (i.e., the level at which spoilage organisms and pathogens are killed and below the level where undesirable organoleptic changes are introduced) to enhance the attractiveness of MAP. The effects of MAP/irradiation on sensory properties, and its effect upon depletion of vitamin content with storage, compared to untreated items, have been examined in detail (Robin).

Series with experiments on MAP/irradiation of chicken and pork to optimize the sensory quality showed that each particular food item requires careful evaluation and that generalisation can lead to incorrect and inappropriate specifications for optimum storage.

Other investigations of cod fillets showed, that the combination MAP/irradiation has a relatively short extension of shelf life and this does probably not economically justify the use of the combination.

In comparison of several different combinations aimed at reducing mould in strawberries the MAP/irradiation treatment showed the best results.

A study on the effects of MAP/irradiation on nutritional quality demonstrates that the deleterious effects of irradiation on vitamins can be removed by modifying storage atmospheres (Robin). Nevertheless all studies have shown that the advantages of MAP/irradiation must be determined for specific applications with a fair degree of caution and requires the ascertainment of exact conditions for every product for microbiological safety.

1.4.3 Irradiation at cryogenic temperatures

A number of studies about food irradiation reported that organoleptic and nutritional quality was improved when food items were irradiated in the frozen state. The benificial effects of low temperature upon organoleptic and nutritional quality has been related to the reductions in diffusion rates.

Table 7. Effect of the temperature during irradiation on retention of A-Tocopherol in rolled oats

Temperature (°C)	mg Tocopherol/100 g non - irradiated	irradiated
50	6.5	3.5
20	7.4	5.6
5	7.5	6.2
- 72	7.7	6.6
- 180	7.6	7.1

Linear accelerator, 5 MeV electrons, 1 kGy, air not excluded, analysis within 24 h after irradiation
Data from `Conference Documention'IBC,London,1990 (Robin)

The low temperatures also confer some extra degree of protection upon the bacterial cells which are the primary target of the ionising radiation. For this reason, higher doses of radiation may be needed in this potentional combination treatment. In one sense this defeats the object of the research, given that the main reason for promoting combination treatments is that they allow radiation dosages to be reduced. Diehl (1990) notes that cryogenic/irradiation applications require a careful technical and cost/benefit analysis before they could be implemented. Their minimal effect upon the food must be weighed carefully against the limitations of bactericidal efficacy that are inherent in the method.

1.4.4 Irradiation and chemical treatment

A further research area is the use of irradiation in combination with conventional preservatives (like nitrite) to reduce the use of these chemicals. Studies with reduced sodium nitrate content in bacon (from 200 mg/kg to 20-40 mg/kg) showed that irradiation is one of the most promising "antibotulism" alternative to sodium nitrate. At the same time the effect on anti-oxidants, colourants, and flavourings has to be taken into account. Irradiation will not always serve all the functions of the preservative. For example, nitrite in bacon also maintains the colour of the product, but the quantity of nitrite required for the nonmicrobial effect might be less than is required to control microbial growth. Combination treatments and the above effects have to be studied more in the future.
But also microorganisms (e.g., *Clostridium botulinum* spores) showed different resistance qualities toward irradiation combined with chemical treament like the additive of NaCl. Studies on canned goose liver showed that by a combination treatment NaCl(2.9%)/irradiation(5kGy), the conventional heat treatment could be reduced by 20 %.

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1.5 Irradiation of packaging material

Irradiation processes can be used for the sterilisation of packaging material (e.g., aseptic filling) or for prepacked foods to prevent microbial recontamination during and after processing.
For sterilisation of packaging material the number of decimal reduction (e.g., D_{value}) has to be chosen depending on the initial count on the surface of the packaging material and the requirements of the subsequent use. A gamma energy (Co-60) treatment of 10 kGy (as is permitted for herbs and spices) results in a 7 decimal reduction of resistant bacterial spores on packaging material (Berg).

Changes in packaging material

Irradiation has created a need for suitable approved packaging materials which can withstand radiation processing. It is important to select materials in which chemicals formed as a result of the radiation treatment do not migrate and interact with the food, affecting its organoleptic and toxicological aspects. It is also important to select materials in which the physical properties are not altered to the extent that they cannot resist damage during commercial production, shipment and storage.
The two major effects of ionising radiation on polymers are cross linking and scission of the polymer chains. In general, these two competing effects occur simultaneously, and the predominating effect depends on the structure of polymer. The net effect of cross linking reactions is to modify the physical properties of the material such as: increasing the tensile strength, hardening, changing the solvent resistance, and decreasing the impact strength. Chain scission involves rupturing the molecular bonds, thus leading to the formation of short chain polymers, evolution of gases and change in migrants.

The known changes in different packaging materials are summerized as follows:
* Metal is not influenced at all;
* Glass shows a discoloration due to induced electron displacement and forming of so-called "colouring centres".
* Natural materials like paperboard and cellulose/cellophane may show brittleness upon a high dosage (at a level of 100-250 kGy).
* Polymers are influenced by cross-linking depolymerization and other processes depending on the polymer type.

Networking and decomposition of low molecular substances can lead to off flavours. Polyvinylchloride (PVC) or polyterafluoroethylene (Teflon) can split off toxical substances.

The dose at which radiation effects become significant for less radiation resistant materials - polypropylene, polyvinylchloride, cellulose, polyvinylidene chloride - is 10 kGy.

Polyethylene - the most investigated polymer- reacts as a consequence of radiation by at first becoming increasingly insoluble (due to the crosslinking) and with increasing doses changes in colour occur. Physical properties including flexibility and oxygen permeation may be altered.

The following table 8 lists the films approved by the U.S. Food and Drug Administration for use in irradiation processing. At the present time, only single layer films are approved for the use in food irradiation.

Table 8. Packaging materials approved by FDA for use with irradiation of foods

Packaging material	Maximum dose (kGy)
kraft paper	5
glassine paper	10
wax-coating paperboard	10
nitrocellulose-coated cellophane	10
vinylidene chloride copolymer (Saran) coated cellophane	10
vegetable parchment	60
vinylidene chloride-vinyl chloride copolymer film (Saran)	-
vinyl chloride-vinyl acetate copolymer film	60
rubber hydrochloride films	10
ethylene-alkene-1 copolymer	10
polyethylene films	60
nylon-6 films	60
polystyrene films	10
polyethylene terephthalate films	60

Special attention is necessary to ensure that migration limits are not exceeded. Even within the limits of the regulations, low levels of migrants may cause off-flavour in food products. Special care is necessary to select a packaging system capable of maintaining the improved quality, because sometimes a part of the system is affected adversely by the gamma energy, like a butyl compound seal used in tins or zinc pigment in the inner layer of tin cans.

On the other hand, improvement of properties of packaging material was found as well.
Better shrinkage properties obtained by irradiation have already been mentioned.
Zehnder (1984) pays special attention to the improvement of a flexible compound package by radappertisation (30-120 kGy). The material strength and the adhesion between the polyester/aluminium/polyethylene layers are, respectively, 30% to 700% better than without irradiation.

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1.6 Current utilisation of food irradiation

During the last 8 years some 30 countries have considered application of food irradiation and given clearances for specific purposes such as sprout inhibition in potatoes and onions, disinfestation of spices, dehydrated seasoning and cereals and decontamination and shelf life extension of tropical fruits, mushrooms, fish, fish products, frog legs, shrimps, pork and poultry products.

The EEC is likely to introduce legislation that standardises food irradiation and permits its trade within the Community. At the moment only the importation of irradiated foods is allowed.
Several tropical countries have completed efficacy testing and are planning food irradiation facilities (Algeria, Chile, Ivory Coast, Cuba, Egypt, Jamaica and Thailand).

Besides food irradiation many of the facilities have a prior capability for irradiation of pharmaceuticals, medical and cosmetic products and can be converted to dual capability in due course. It may also be observed that countries which are not sympathetic to food irradiation- such as Sweden, Australia, Germany and New Zealand- also have facilities available, which serve for research and evaluation purposes.

At present only 19 countries out of the 36 permitting irradiation actually conduct commercial irradiation. The total commercial market is now some 500,000 tonnes per annum, as indicated in table 9.

Table 9. Practical application of food irradiation

Country	Food item	tonnes/annum
Argentinia	spices, cocoa powder, spinach	50
Belgium	spices, dehydrated vegetables,frozen foods	8-10,000
Brazil	spices	200
Chile	onions,potatoes,dehydrated vegetables,chicken	500
China	potatoes,apples	500
Cuba	potatoes,onions	500
Finland	spices	not known
France	spices, poultry,vegetables,seasonings	5,800
Hungary	spices	400
Israel	spices	120
Japan	spices	15-20,000
Korea Rep.	garlic powder	not known
Netherlands	spices,frozen foods,poultry,dehydrated vegetables,egg powder	18,000
Norway	spices	not known
South Africa	fruits, potatoes,onions	> 21,000
Thailand	onions,fermented sausages	600
U.S.A.	spices	3,300
USSR	grain	400,000
Yugoslawia		> 100

Data from Joint FAO/IAEA Division, Food Preservation Section. IAEA, Vienna (Robin).

Several countries irradiate single items (e.g., Russia irradiates only grain and Japan only potatoes). Nations that permit irradiation to a wide range of foods, such as Israel and Thailand, actually produce very little commercially. Unfortunately, there is no official data on South African production, where the widest range of food items may be irradiated.

ECC members like The Netherlands and Belgium are geared more to export than domestic consumption. The tonnages of food treated per annum are small in proportion to the total consumed, but there are numbers of restraints. Thus for example, in the Netherlands, companies that export a great deal of their products to countries that ban irradiated foods (e.g., Germany) do not irradiate foods in fear of destroying their export market.

In France, two facilities now approaching completion will provide a capacity of 15,000 tons each by 1993, and two more projects in planning will add another 25,000 tons per year. Thus, with consumer acceptability not a major problem and with a large amount of capacity available, food irradiation in France looks ready for rapid growth (Campbell).

In the other ECC member states the issue of consumer concern underlies the restricted development of food irradiation. The sensitivity of governments and food producers to public concern of food irradiation has caused the development of the process to be slow and piecemeal. Some of these states (Germany, Italy, Spain, Denmark) are awaiting a directive from Brussels to open their market to food irradiation.

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1.7 Economics of Irradiation

1.7.1 Irradiation facilities

Despite the encouragement of international studies, progress in the commercial development and use of the progress has been slow. A major deterrent is the considerable capital investment entailed in setting up an irradiation facility. A small pilot plant costs $1.2 million while current estimates for a fully operable plant run to $ 5 million (Teale).

Table 10: Capital costs (U.S. dollars) for a Cobald-60 one megacurie installation

Irradiator installed	900,000
Cobalt-60 (one megacurie)	1,070,000
Rental of source container	12,650
Shipping charges	40,000
Local labour required for installation (100 h)	25,000
Radiation shield	450,000
Detailed drawing for shield	24,400
Total	2,522,050

Ley (1985) in Food Irradiation, NEB, Dudlin after Cuba (1984)

As long as only one or two foodstuffs are licensed to be irradiated, it is hardly possible to fully utilize an irradiation plant, particularly if the license concerns a seasonal product available for irradiation for only a few weeks per annum. Without government subsidies, a commercial utilization of this method on a large scale as is presently carried out in Japan for potato irradiation, would probably not be in operation. Only if a larger number of products is cleared in many countries, this method will become economically interesting. But the current climate of consumer distrust in some countries coupled with the barriers to free trade in others is discouraging.

The world's largest builder of industrial irradiation plants for food and medical sterilisation is the Canadian Company Nordian International. Nordian estimates the world total plants to be 143, of which it has built 83.

Table 11: Builder of industrials irradiation plants (Butcher)

Company	Home country	Number
Nordian	Canada	83
AEC	USSR	11
Marsh	UK	11
Radiation Sterilizers	USA	6
Conservatome/SGN	France	5
JAERI	Japan	4
Sulzer	Switzerland	4
Radiation Technology	USA	4
CNEA	Argentinia	3
Isotron	UK	2

(Source: Nordian International)

1.7.2 Irradiation process

Operating cost is made up of depreciation of the plant, the source, and the labour. The most variable part of this sum is the depreciation of the source, which is strongly influenced by the plant efficiency. Using Cobalt-60 the yearly loss of activity amounts to 12 % . In a large facility with 1 Mio. Curie and the price for cobalt 2 swiss franks/curie it comes to a loss of activity of 240,000 swiss franks per year (Wolpert).

Food irradition involves high capital costs but much lower energy costs than canning or freezing. There are large savings at the wholesale and retail levels.

Table 12. Energy consumption for certain preservation techniques (Kampelmacher)

treatment	energy consumption
5.5 days refrigerated	318 KJ/kg
heat sterilisation	918 KJ/kg
freezing	7.552 KJ/kg
irradiation (3kGy)	17.5-95 KJ/kg

The energy costs of irradiation are 70-80% less than the cost of conventional techniques such as canning, and it also offers enormous post-processing savings because refrigeration costs are eliminated at the wholesale and retail levels, as well as at transport (Dempster).

The expenses for irradiation are strongly dependent on the capacity and the running continuity of the facility. Most of the estimated expenses are only correct, if radiation facility is kept running through the entire year (Grünewald).

A list of the estimated costs for the different fields of application are summerized in table 13.

Table 13. Estimated costs for food irradiation

Kind of treatment/ product	costs	share of costs of final product	source
<u>Low dosis range (<1 kGy)</u>			
general	.03-1 US cents/kg	0.7-7 %	Sulzer
general	0.20 DM/kg		Herrnhut
sprout inhibition (onion)	1.48 US cents/kg		Kampelmacher
sprout inhibition (potato)	0.7-0.8 US cents/kg		Grünewald
apples or cherries	1.1 US cents/kg		Brown
strawberries	4 p/kg		Northern Ireland
fruits	0.3-0.6 US cents/kg		Herrnhut
rice	0.2-0.6 US cents/kg		Herrnhut
grain	3.2 US cents/kg		Grünewald
grain	3.3 US cents/kg		Kampelmacher
trichina safe pork	2.2 US cents/kg		Brown
<u>middle dosis range (1-10kGy)</u>			
general	.03-10 US cents/kg	0.3-5 %	Sulzer
hygienisation of poultry:			
	5.4 US cents/kg		Grünewald
	4-7 US cents/kg		Herrnhut
	5.5 US cents/kg		Kampelmacher
	1.5 p/kg		Nordian/Butcher
	0.5 p/kg		Marsh/Butcher
	5.0 p/kg		Gamaster/Butcher
	1-2 p/ kg		Northern Ireland(19)
extension of shelf life of fish	4-7 US cents/kg		Herrnhut
decontamination of spices	10.8 US cents/kg		Grünewald
	4-7 US cents/kg		Herrnhut
	11 US cents/kg		Kampelmacher
decontamination of cacao	6-7.5 US cents/kg		Herrnhut
<u>high dosis range (20-50 kGy)</u>			
general	2-20 US cents/kg	0.2-2%	Sulzer
medical supplies	0.60 DM/kg		Grünewald
	7.7-13 US cents/kg		Brown

In Vannes (France) 1978 a plant for irradiation exclusively of poultry meat was put into operation and equipped with an electron linear accelerator. An economical operation was calculated already in the first year of operation with an output of 4500 t per year.

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1.8 Legislation, control, statement of international commissions

1.8.1 ECC-regulation and control of food irradiation

National legislation on food irradiation within the EEC varies considerably and in some countries it is totally lacking due to several unique political factors.
At the moment, food irradiation is accepted only by one half of the EC members. Acceptance of food irradiation by Western European nations outside the EC is extremely limited.

This creates problems of barriers to free trade. This is the situation that has obliged the Commission to draw up proposals to harmonise national legislation targeted for 1992.

In 1986 the EEC Scientific Committee for foodstuffs produced its findings on food irradiation which recommended clearance for food irradiation under certain conditions relating to specific applications, doses and food classes provided there were strict controls. In response, in 1987 the European Parliament rejected on precautionary reasons the general authorisation of irradiation as a method of conserving food and called for a ban on imports of irradiated food and animal feed from non-Member States (Doc A2-216/86 of the European Parliament).
While accepting that irradiation could complement traditional methods of conservation and processing, the parliament called for a study of alternative methods which could replace irradiation in Member States. The resolution stressed the importance to develop means for detection of irradiated foods and noted that if the Commission would propose free trade in irradiated foods it would have to be a system of compulsory labelling.

In December 1988 a proposal was published that irradiation should be permitted for a wide range of foodstuffs. A directive authorising irradiation of a specific list of products (11 classes including spices), with provisions, maximum dose for each class and controlling irradiation facilities, has been submitted by the Commission to the European Parliament and to the Economic and Social Committee. This guiding rule should be put into force in 1993. It is demanded that the irradiation of food is done only with radiation plants which are under official control. Further, every product must be labelled as radiated. The official control of the radiation plants should enforce the correct irradiation also after an export of the foods. Because there are hardly any possibilities to prove irradiation of a product afterwards, the control of the correct irradiation in the plant and the correct marking would be a way to enforce the labelling and consumer information.
This proposal was made against a backdrop of the European Parliament's vote against approval of food irradiation on cautionary grounds. This was followed in 1989 by a proposal of a general ban on irradiated foods, with the single exception of spices. Currently there is no consensus among the legislation of certain EC members and the current status as shown in table 14.

Table 14. Current legislation for food irradiation in Western Europe (Robin)

Country	Type of acceptance	Food item	Max. Recommended Dose (kGy)
Belgium	provisional	garlic	0.15
		gum arabicum	10
		onions	0.15
		paprika	10
		pepper	10
		potatoes	0.15
		shallots	0.15
		spices	10
Denmark	unconditional	potatoes	0.15
		spices/herbs	15
France	unconditional	cereal products	5
		fruits (fresh/dried)	5
		gums	10
		poultry	5
		spices	5
		vegetables (fresh/dried)	5
	provisional	garlic	0.15
		onions	0.15
		potatoes	0.15
		shallots	0.15
Italy	unconditional	garlic	0.15
		onions	0.15
		potatoes	0.15
Netherlands	unconditional	chicken	3
		onions	0.05
		potatoes	0.15
		sterile hospital diets	25
		egg powder	6/7
		fish (frozen)	6
		frog's leg(frozen)	5
		malt	10
		rice products	1
		rye bread	7
		shrimps (cooked/frozen)	7
		spices	10
		vegetables	10
	test market	butter mix (powder)	1.5
		endives	1
		fish fillets	1
		meat (minced)	not specified
		potatoes(peeled)	0.5
		shrimps	1

Country	Type of acceptance	Food item	Max. Recommended Dose (kGy)
		vegetables(fresh)	1
		vegatables(frozen)	0.75
	experimental	asparagus	2
		cocoa beans	0.7
		onions	0.15
		poultry	3
		strawberries	2.5
Spain	unconditional	onions	0.05
		potatoes	0.15
UK	unconditional	sterilised hospital food	not specified
		strawberries, seafood,spices	to be specified from 1991
Finland	unconditional	herbs/spices	10
		sterile hospital diets	not specified
Norway	unconditional	spices	10

The EC members Ireland, Greece and Portugal currently do not permit irradiation. It is supposed that they will not oppose the 1992 harmonisation directive. Germany (which was the first country to allow irradiation of spices in 1957, only to ban such irradiation in 1958) no longer accepts irradiation. Likewise, it is expected that Germany and Denmark will bow to EC pressure and accept the 1993 directive.

1.8.2 Handling and regulations of labelling

Irradiated food cannot be recognized by sight, smell, taste or feeling. The only safe way for consumers to recognize irrradiated foods is to carry a label that clearly anounces the treatment in words, a symbol (radura symbol) or both.

It has been suggested, partly by the industry and governments, that irradiated food should not be specially labelled, the argument being that other forms of food processing are not identified on the label (e.g., chemical treatment), that irradiated foods do not present any hazard that people need to be aware of, and that consumers might hesitate to buy food products identified with the word "irradiated".

On the other hand consumer surveys in the USA about the influence of labelling on the consumer reaction have shown that there was a marked influence of informative labelling (e.g., irradiated to control microorganisms) upon willingness of consumers to buy irradiated foods. The authors conclude that the surveys provide clear evidence for the potential influence of labelling on consumer perceptions of food irradiation and their intentions to purchase.

At the moment, irradiated food in its final form must be labelled as such when sold in France, Belgium or the Netherlands. The Netherlands requires a "Radura" symbol; in Belgium, foods are labelled with this emblem on the whole sale level and retail labels are optional. Processed food containing irradiated ingredients does not need to be labelled.
Regulations in some countries (e.g., Denmark) demand complete labelling, for instance not only of irradiated spices (first generation). The matter is more complicated with the labelling of a pre-packed meal where some individual ingredients such as spices may have been irradiated (2nd and 3rd generation). Practically a control of this regulation is not feasible, not least because of the lack of any agreed method for detecting of irradiation in the 2nd or 3rd generation. As a result Danish food industry does not enforce the regulation.

The U.S. Food and Drug Administration has dropped its labelling proposal for retail packages because irradiated foods " have already been shown to be safe".

Both sides of the debate agree that irradiated food should be labelled although there is debate about the amount of information the label should carry. France is currently the EEC country opposed to extending the labelling requirements for foods containing irradiated ingredients.

The International Consultative Group on Food Irradiation (ICGFI) has developed guidelines for the labelling since 1984 and has recommended the labelling of irradiated foods supported by public information and education campaigns designed initially to help consumer decide whether they want to buy radiated foods.

1.8.3 Regulations for approvement of irradiation and technical equipments

Extensive regulatory and administrative procedures to strengthen the controls on commercial use of food irradiation were developed by the International Consultative Group on Food Irradiation (ICGFI) established under the agis of FOA, IAEA and WHO since 1984. ICGFI has produced a number of guidelines/codes of practise to assist national authorities in regulating the commercial use of irradiation:

1. Codes of good irradiation practice for specific application of food irradiation
2. International inventory of authorised irradiation facilities
3. International training programs for operators/plant managers of irradiation facilities and food inspectors
4. International Dose Assurance Service (IDAS)
5. Labelling
6. Certificate of irradiated food

1.8.4 Codex Alimentarius Commission and other committees

In 1962, FHO and WHO founded the "Codex Alimentarius Commission" with the goal to harmonise the food legislation by establishing international accepted standards and to facilitate the foreign trade. The commission has about 120 member states. By Joint Expert Committee Report on the wholesomeness of Irradiated Food (1977 and 1981) a general authorisation would be given to allow irradiation of any food to an overall average dose of 10 kGy.

Based on the knowledge and experience gained in this project the Codex Alimentarius Commission issued in 1983 a general international standard for irradiated food as well as recommendations for the operation of irradiation facilities, to facilitate the international trade with irradiated foods. Currently the "International Standard of Labelling of Irradiated Foods" is revised by the Expert Committee of the Codex Alimentarius Committee.

In 1984 the "International Consultative Group on Food Irradiation" was founded and is meanwhile joined by 28 governments. The secretariat of the Group is kept at the IAEA in Vienna. The goals of the group are: to observe and to assess the developments in the field of food irradiation, to serve the exchange of information between the member states and to offer help for decisions of the Organisations like the WHO and the Codex Alimentarius Commission.

1.8.5 Attitude of the World Health Organization

The WHO regards food irradiation as a contribution to public health:

"Food irradiation is a technology that can, under certain circumstances, be safely used to help control two of the most serious problems connected with food supplies":

Foodborne Illness

A relatively high percentage of raw foods of animal origin are contaminated by pathogenic bacteria and this results in high levels of foodborne illness in all countries for which statistics are available. Among the factors that appear to account for the increases in foodborne disease

- are explosive growth in the mass rearing of food animals,
- polluted environments,
- mass production of foods of plant origin,
- increasing international trade in food and animal feed,
- and the large-scale movement of people as guest workers, immigrants and tourists.

Food losses

In countries with warm climate the estimated storage loss of cereal grains and legumes is at least 10%, with nongrain stables, vegetables, and fruits, the losses due to microbial contamination and spoilage are estimated to be as high as 50%. In commodities such as dried fish, insect infestation is reported to result in a loss of more than 25%. With a rapidly expanding world population, any preventable loss of food is intolerable.

The WHO has pronounced several times that food irradiation is not injurious to health and that it is worthy to be advanced. In a press release of the WHO (In Point of Fact No.40/1987): "All countries not regarding their state of development are encouraged to use food irradiation. The process offers not only a bigger range of unobjectionable food, but also the advantage to reduce the dependance on chemically treated foods".

1.8.6 Current international food irradiation initiatives

FAO/IAEA have set up technology transfer programs in the Pacific, South America, Europe (i.e., its developing countries), the middle East and in Africa. A breakdown of the various schemes is shown in table 15. In the pilot-scale studies noted in the table, emphasis was placed upon direct economic benefit being derived from the problem addressed by irradiation.

Thus, in the Pacific (RPFI) region, the disinfestation and decontamination of stored food products, improvement in hygiene of seafood, quarantining of fruits, and sprouting of root crops were addressed in the programs initiated with local food industries over the period 1980-1988. The success of these programs has led to the construction on a large scale of demonstration and commercial irradiators.

In South Africa , a similar program, designated as LAFIP, has been in operation since 1986. LAFIP identified the major post-harvest losses to be addressed by irradiation programs, and this program is currently under way.

The program targeted upon southern and eastern Europe and the Middle East addresses problems associated with a wide variety of temperate and semi-tropical crops. Since there is a variation in the extent of technical development in the participating nations, the emphasis extends from quarantining at one extreme to extending shelf-life at the other. A considerable effort is being expended upon pilot scale studies, marketing initiatives and promoting the harmonisation of legislation.

In Africa, on the other hand emphasis has been placed, since initial reviews in 1986, upon studies of the infrastructure required for the development of food irradiation. Despite the complexity of the food shortage position, it is clear that post harvest losses are a major contributing factor. The FAO/IAEA studies made clear that food irradiation in Africa can only influence the situation positively where an efficient and o.k. infrastructure exists. In Africa, there are many `low-technology' steps to be taken to aid efficient planting, harvesting and crop collection before irradiation could become viable (Robin).

Table 15. FAO/IAEA technology transfer initiative (Robin)

Area	Organisation	Countries Involved
Europe/Middle East	FAO/IAEA	Bulgaria, Czechoslovakia Hungary, Iraq,Iran, Jordan Poland, Syria, Turkey
Global	International Facility for (IFFIT) FAO/IAEA-Dutch Ministry of Agriculture	Based in the Netherlands, provides feasibility studies FAO/IAEA member states

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1.9 Consumer reactions to irradiated food

Success or failure of food irradiation will ultimately depend upon consumer acceptance or rejection of the process. Consumer acceptance reflects the understanding of the purpose and effects of irradiation.

Research on the attitudes of consumers often led to other results, than the opinion represented by the media.

To find out about the consumer's reaction towards irradiated food years ago, consumer polls were made on a small scale. In all countries and independent of the product, positive reactions to irradiated foods have been met with only a few exceptions. In September 1986 and in March 1987, irradiated mango and papaya fruits were offered marked as irradiated in some U.S. food stores. Two thirds of the consumer were willing to buy the irradiated fruits.

In France 1987 irradiated strawberries were sold during a consumer test, they were given a freshness guarantee for 4 days. Because of the better quality many consumers were willing to pay a 30% higher price for the irradiated strawberries.

The consumers in the European Community group estimate that between a quarter and a third of people in countries where food irradiation is legal would accept irradiated foods.

U.S.A. studies to measure public acceptance, show that the majority of people are willing to try irradiated foods. But the overwhelming amount of responses are in the "probable"- categories which indicate a considerable lack of intensity of feeling. Also the number of people willing to try irradiated food increases significantly after the presentation of information about food irradiation. The finding, that individuals are more favourable toward irradiated food than they think other people are, is consistent with the experience in organizing the focus groups and in recording the discussion (Bord, Bruhn).

Consumers showed a higher level of concern for preservatives and sprays than for irradiation. The study suggests that traditional consumers' attitudes towards food irradiation can be positively influenced by an educational effort, but not those consumers already strongly opposed to the process. Willingness to buy irradiated food was based on the safety of the process rather than the advantages for any specific food product (Bord, Bruhn).

Studies about consumer acceptance of irradiated papaya showed that the consumer will accept a high-quality, FDA-approved product. The degree of acceptance was noteworthy. This supports the concept that people will accept the safety of food labelled as FDA-authorized and will buy a product of good or superior quality (Bruhn).

Attitude studies suggest acceptance of irradiated foods, but more consumer information is needed (Bruhn).

The general lack of information about irradiation promotes uncertainty in those asked to assess its degree of acceptance. Although individuals are ambivalent towards irradiated food, there is a strong tendency to view public opinion as opposed. Those who know something about food irradiation tend to have more acceptance of it. Learning that other people have safely used irradiated food also increases acceptance. This pattern of results seems to indicate the extent to which the public ultimately accepts or rejects irradiated food may well be predicated on the presence or absence of information about the topic and the type of information that reaches the public.
In the Netherlands irradiated foods have been on the market for 20 years, and some 15,000 tons are treated each year. Despite this background, 35% of those interrogated had little or no knowledge of irradiation, and only 11% had a reasonable good understanding. Under these conditions, the fact that 34 % were favourable to irradiation can be considered significant. In any case, a clear majority preferred irradiation to the use of chemicals.
In Belgium is virtually no public discussion and little awareness.
In France there is perhaps a core of 10% who are opposed to irradiation by principle, at the other end of the spectrum are perhaps 20% who would buy enthusiastically, informed and convinced of the benefits. The others are indifferent, but would have no reluctance to buy an apparently better product.
In Great Britain different results about consumer reactions exist. A recent article of the London Food Commission, a lobby group said that 85% are opposed. Another survey shows 25 % in favour and a large number who are indifferent.

The International Organisation of Consumer Unions (IOCU; consisting of 170 consumer organisations drawn from 70 member states across Europe, Asia and Latin America) has demanded a worldwide moratorium on use or development of the technique pending the establishment at independent detection tests and rigorous international control over labelling. They are also concerned about the lack of exhaustive safety testing and the potentially harmful materials that may be produced by the irradiation on pesticide and herbicide residues in food, and plastic packaging materials in contact with the food.

The further development of food irradiation depends mainly on the acceptance of irradiated food by the consumer and on the readiness of food industry to use the process.

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1.10 Detection of prior radiation

The absence of a reliable detection method of prior irradiation was often used as an argument by the opponents of the process not to authorize food irradiation. Indeed the previous research showed, that the detection of prior irradiation of food is a difficult problem. This is largely due to the irradiation process up to 10 kGy having little discernible effect upon food. The created radiolytic changes are not definitively from irradiation, they are common to other preservation processes. Additionally, many of the radiolytic products are transient and present in trace quantities. For this reasons, there was not a reliable method to identify the previous history of a given food.

The present research has changed to the state, that some sensitive diagnostic techniques for certain foods look to be very promising. Various routes towards this goal are currently the subject of intensive research. In table 16 a number of promising methods, the detectable chances of irradiation and the relevant food are listed.

Table 16. Diagnostic techniques for the detection of prior irradiation (Delincee)

Technique	irradiated caused changes	food items
alkali eluation	nucleic acids	lobster
chromatography:		
thin layer	carbohydrates, proteins (derivated products)	grain, flour, fish
gas	volatile products (aroma compounds)	spices
gel	proteins	meat
high performance liquid	proteins, lipids (derivated products)	meat, poultry
ion exchange	protein (derivated products)	meat, poultry, fish
genetic fingerprinting test	genes	grain, strawberries
colorimetry	carbohydrates, proteins, lipids potatoes, meat	grain, flour,
electrical conductivity	membran permeability	potatoes, fish, fruits, vegetables
electron spin resonance	dry substances (free radicals)	meat, fish including bones
electrophoresis	proteins, nucleic acid	meat, fish
enzyme activity	enzyms, metabolism	meat, potatoes, fruits, mushrooms
fluorimetry	nucleic acid, proteins	meat, fish
tissue culture	metabolism	potatoes, onions, mushroom
gradiated centrifugation	nucleic acid	poultry
thermoluminescense	dry substances (free radicals)	spices, seasonings dried vegetables
microbiology	micro flora	meat, fish, strawberries
microscopy	structure, cell wall	potatoes, fruits
viscosimetry	membranes, carbohydrates	spices, dried vegetables, meat

Principles of the most common methods

Irradiation generates a wide range of free radicals. These primary radicals will undergo a variety of reactions with food components, producing secondary radicals or end-products which may prove diagnostic of the prior irradiation. Since water is a major component of most foodstuffs, the primary radicals generated by the radiolysis of water provide potential targets for identifying prior radiation. These include hydroxyl radicals (OH^{-}), hydrated electrons ($e_{a}qu$), monatomic hydrogen (H^{+}). Secondary radicals can arise from the interaction of the above with oxygen present either in the food or in the atmospheric interface: superoxide ions (O_2), hydrogen peroxide (H_2O_2), molecular hydrogen (H_2). The high reactivity of these free radical species prohibits against their direct utilisation in diagnostic tests for prior irradiation. Most techniques currently being developed rely upon detection of secondary or tertiary free radical modification of particular food components, and at present the most promising species are:

* Aromatic compounds
* DNA (Disoxyribonucleic acid)
* Carbohydrate modification
* Inorganic food components such as bone

In addition to the chemical markers further detection methods are based on changes of the physical properties (e.g., electrical properties) or microbiological flora.

Aromatic Compounds

Currently attempts to identify radiolytic products with chromatography have shown some promise because this technique is very sensitive and the necessary analytical hardware is available. Although this technique is expensive and complex it is widely used as a trace analytical device and so ideally suited to wide scale adoption. The second generation of hydro-aromatic molecules which occur in many different kinds of food (e.g., phenols) can be detected by chromatographic techniques, such as High Performance Liquid Chromatography (HPLC) or Gas Chromatography-Mass Spectrometry (GC-MS). At present, the most promising of the aromatic markers is the mixture of tyrosine isomers. As a protein component it will obviously be present in appreciable concentrations in foods with substantial protein content. Problems of interpretation arise in irradiated animal tissues where the tyrosine isomer profile is influenced by the action of hydrolysing enzymes.

Modification to DNA Profiles

DNA is a component of most animal tissue, and it is vulnerable to attacks by hydroxyl radicals. The derivated products can be isolated and identified by HPLC or GC-MS. Although this approach holds considerable diagnostic promise, it currently does not lead to rapid and simple development, since it requires expensive instrumentation and skilled analysis. New methods of promise are emerging, such as pulsed field electrophoresis and the use of DNA probe techniques (Delincee).

Carbohydrates modifications

The observation that irradiation of colloid starch, cellulose and pectin decreases their viscosity has revealed a secondary marker (N-acetylglucosamine (NAG)) in detecting irradiation of spices. This research has utilized a sophisticated variant of the technique of nuclear magnetic resonance (NMR). While NMR has powerful applications in this kind of detailed organic analysis, it has a relatively high detection threshold, lacking the sensitivity of chromatographic analysis and the related magnetic resonance technique of ESR. Among the complex glucosamine carbohydrates which are accessible to this approach is chitin (present in prawns and shrimps). NMR is also used to study radiolytic damage in simpler carbohydrates such as sucrose. This has a wide potential application in detecting prior irradiation of milk products and fruits. The already widely used application of NMR is expected to extend for use in the identification of prior irradiation (Robin).

Thermoluminescence technique and electron spin resonance

Two of the most promising methods are thermoluminescence (TL) and the electron spin resonance (ESR) spectroscopy. Both techniques are extremely sensitive, capable of detecting very low radiation doses and they depend upon identifying electrons produced by primary impact.

electron spin resonance
trapped electrons
measured directly by
spectroscopic techniques

↗

Food --------> *ionising radiation* --------> *electrons released* *trapped in inorganic components*

↘

thermoluminescence
electrons released by heat
combined with activation
centres to produce light

Figure 1. Potential Detection of Previous Irradiation by Thermoluminescence (TL) and Electron Spin Resonance (ESR) (Robin).

Thermoluminescence technique

The application of thermoluminescence is specially used for inorganic materials, such as minerals (e.g., spices contaminated with dust and sand or extracted minerals from foods). Its reliability, however, is reduced considerably when dealing with organic substances. Nevertheless, a substantial research effort has been expended on TL because of the strength and simplicity of the technique.

Electron Spin resonance technique

Electron spin resonance is widely used to study free radicals. Its sensitivity is far greater than NMR, but somewhat lower than TL. As in thermoluminescence, attempts to use electron spin resonance have concentrated upon inorganic food components, particulary meat or poultry where the bone component can be utilised as the electron trapping medium.

Electrical impedance measurement

For potatoes, the measurement of the electrical impedance turned out to be a promising detection method. An electrode is positioned between the two ends of the potatoe and the factor (ratio) between the impedance of different frequences is measured. This effect of irradiation is probably caused by changes of the cell membrane, but these effects were not sufficiently investigated. By the electrical impedance method the applied radiation dose can be estimated up to a storage time of 6 months.

Epifluorescent Filter Technique (DEFT) and Aerobic Count (APC) Method

One of the most promising techniques of the microbiological methods is the combination of epifluorescent filter technique and the aerobic count method. The detection of irradiation by this method is based on the comparison between total count and the number of cells capable to duplicate. In raw food samples the counts of the fluorescent microorganisms (using DEFT for detection), correlate well with traditional Total Viable Counts (TVC), of organisms able to grow on a nutrient medium. Work has shown that if foods are irradiated the DEFT count of microorganisms remains at the unirradiated level, whilst the TVC is reduced. The application of these methods has been done on a variety of meat, fish products (particular frozen), milk, herbs and spices.

Although the intensive research work in international groups, (e.g., Commission of the European Communities) there is not a satisfactory routine and universal method to identify prior irradiation. Also, none of the present methods is applicable for determining the applied radiation dose.

Through combining different procedures a higher probability of identifying irradiation can be achieved. But it is much more difficult to identify irradiated components within complex foods.

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2 Identification of remaining knowledge gaps

Despite the encouraging international studies, progress in the commercial development and use of irradiation has been slow due to several reasons. The results available, the need of further research work is regarded rather differently from the various interest groups -industry, consumer, government.
Major deterrents for the **food industry** are high capital investments entailed in setting up irradiation facilities and consumers' considerable reservation. Use of more favourable treatments (e.g., the cheaper chemical additives for inhibition of sprouting or insects) hinder the use of irradiation technology. As long as irradiation is banned or only one or two foodstuffs are licensed to be irradiated, the irradiation process becomes hardly economically interesting.
Reason for **consumer perceptions** addresses the wholesomeness aspect of irradiated foods. This is a result of contradictory press reports about safety and wholesomeness of irradiated foods and the lack of consumer education about irradiation food technology.
Official bodies hesitate with the broad authorization of food irradiation due to the insufficient controls of the licensed dose and detection methods of irradiated foods.

In spite of many political factors the following **remaining knowledge gaps** should be filled in order to eliminate above mentioned doubts and uncertainties.

2.1 Process and facilities

The irradiation process, using **radiation sources**, has proved very successful on a large scale in the sterilisation of medical implements (especially of one-way implements, such as injection syringes, tubes, catheders etc. which as made of plastics). After an experience of 20 years with irradiation techniques, observance of irradiation procedures are now routine in this industry. On the basis of this existing knowledge irradiation of food has become commercial practice in a number of countries.

In the area of the process and facilities remaining knowledge gaps are mainly cited
* in the application of electron accelerators and
* in the practical measurement of the absorbed dose.

2.1.1 Electron accelerators

The use of electron accelerators for the irradiation of free-flowing bulk quantities of food (e.g., grain and spices) on an industrial scale is still an area under study. Only one large installation (radiation disinfestation of grain in Odessa) is known to have been in operation for several years (Ehlermann). In

contrast to the usual radiation processing of packaged foods, bulk materials like grains are usually handled at high throughput in elevators or pneumatic transport systems.
Further research for trouble-free industrial application is necessary.
* Radiation processing must be integrated into existing handling systems and this be adapted in such a way that optimization of homogeneity of dose distributions can be realized.
* The radiation treatment of bulk quantities combined with the transport system causes special difficulties like reliable dosimetry and reproducible results.

2.1.2 Dosimetry

In the field of industrial application further research is required to determine the accurate dose distribution.

The variation of absorbed dose with depth of absorbing material has important consequences for the uniformity with which any product can be irradiated. The recommendation by the Joint Expert Committee on Food Irradiation (WHO/FAO/IAEA) was that food irradiated up to an "overall average" of 10 kGy should generally be released for human consumption as long as the maximum dose does not exceed 15 kGy. It is very difficult to measure in practice this "overall average" and it requires the distribution of a large number of dosimeters throughout the product box. Computations of absorbed doses are possible. But, in general, experimental dosimetry is more accurate owing to the intrinsic heterogeneities of the radiation field and of the absorbing matter. Because of this difficulty an approximation is often made for gamma irradiation with average dose taken as $(D_{max} + D_{min})/2$. This approach becomes increasingly inaccurate as the overdose ratio increases and can lead to average doses being overestimated by about 20% at an overdose ratio of 3 (Sharpe).

Dose variations in electron beam irradiators are much more difficult to predict and dependent upon each product unit (Sharpe). For the measurement in free-flowing systems the importance of using non-toxic dose meter material is stressed, because the dose meters are suspended in the stream of the food particles.

Furthermore the routine measurement of radiation is affected by many external factors, such as dose rate, temperature, humidity, fading as well as other factors.

An assessment of received radiation dose is necessary for several reasons. The main reason is for process optimisation, design and control of process parameters such as conveyor speeds or the bulk flow. An on-line quality control point to measure the received radiation dose within food items is necessary to ensure that the required dose has been delivered.

For the routine measurement of the exact dose **further optimisations for the determination of the radiation dose** are necessary,

* especially in the dosimetry for electron beam accelerators,
* on testing of effects of external influences,
* on development of reliable types of dosimeters and measuring systems.

2.2 Wholesomeness aspects

Extensive literature supports the conclusion that food treated with licensed radiation doses is not related with any toxicological, microbiological or nutritional problems. Remaining gaps of information on the wholesomeness of food are summerized in the literature:

* nutritional and sensory aspects of "complex" foods
* wholesomeness of food treated at doses over 10 kGy
* toxicological aspects in the field of detection of radiolytic products
* nutritional, microbiological and sensory investigations of combined processes
* microbiological criteria for irradiated foods, especially the quality assurance before and after the irradiation process.

To fill the remaining gaps the following reasons are mainly given in the literature.

2.2.1 Nutritional aspects

A great deal of information has been published on the effects of irradiation on various nutrients such as vitamins, amino acids and other nutrients. But, much of these have been "model system" studies involving irradiation of single, pure nutrients. Such studies tend to show more destruction than that which occurs when the same nutrients are irradiated at far lower levels in the complex foods actually consumed.

But there is a lack of information on nutritional aspects of "complex" foods as well as in comparative information about the nutritional quality of food processed by other methods.

Moreover, all forms of food handling and processing result in some nutrient loss in many instances, in-home preparation causes significant damage to nutrient levels.

* Therefore conclusions about the nutritional consequences of irradiation processing should be based on real-life studies involving foods under customary conditions of purchase and use.
* Also the effects of irradiation in combination with other food-processing treatments should be investigated in more detail. The effects of irradiation should be compared with the results of other traditional processes applied in the same circumstances.

* Furthermore more research is required on the effects **of dose over 10 kGy**. According to the opinion of many experts, clarity is needed on the changes of the nutritional quality caused by irradiation used for sterilisation of foods.

2.2.2 Toxicological aspects

The Joint FAO/WHO Expert Committee came to the conclusion after an analysis of animal feeding studies, that food irradiation generally in the "low" and "medium" dose ranges (absorbed radiation up to 10 kGy) is not injurious to health. Regarding the mass of research results, the committee stated that further toxicological investigations for doses up to 10 kGy are not necessary.

Some authors say that successful animal feeding trials cannot necessarily be translated directly to human consumers due to insufficient research to indicate whether subtle long term effects will occur from consumer exposure to irradiated foods (Robin).

Therefore in recent years, radiation chemistry has been recognized as an additional tool for toxicological evaluation, and the methods involved have been substantially refined.
Overall there are a lot of data concerning the safety of irradiation.
Nonetheless most of the specialists have mentioned that data of **radiolytic products** must continue to be collected. If new types of products are considered, data are lacking in:
- the identification of unique radiolytic byproducts from new types of products,
- the interactions between the different food components and their radiolytic byproducts,
- the nature and quantity of nonvolatile byproducts,
- the understanding of the chemistry of radiolytic byproducts in the food matrix and their role in biological processes,
- the investigation of the potential of radiolytic product formation from contaminants such as agrochemicals,
- some basic investigations of the potential of the radiolytic products to interact with the immune system and to reach the fetus and newborn (Gaunt).

2.2.3 Microbiological criteria

It is unanimously recognized by health experts that food spoilage and contamination with pathogens are significant health hazards all over the world. Extensive literature showed that radiation treatment at doses that do not cause unacceptable changes in organoleptic qualities can affectively eliminate potential pathogenic non-sporing bacteria (e.g., in red meat, poultry and fishery products) under normal commercial conditions for products which are marketed in both fresh and frozen stage.

Because these products are usually not sterile, hygienic problems by improper handling can occur (e.g., by insufficient cooling). Similarly with other food processes it is necessary to define microbiological critical control points for Good Manufacturing Practice (GMP) in food irradiation. Still there exists some lack of reference values for a microbiological quality assurance before and after the irradiation process.

* **Safety questions** need to be addressed in the following problem areas:
- how should the raw product to be controlled in relation to the radiation effects?
- How should the irradiated product to be handled after the process (necessary storage conditions in distribution?
- What are the criteria for fixing the expiry date?
- In which way were particular spoilage organisms effected by the irradiation process (e.g., lactobacilli group in vacuum-packed meats)?
- Under which conditions do these microoranisms become important and what do preventive measures look like?
- How can storage quality be evaluated compared to other preservation processes (e.g., preservations)?

* A further potential problem may be that low dose rates encourage the development of mutated bacteria. It could be possible that mutated pathogens produced in this way will be more deleterious than the orginal forms.
Moreover, the analogy with the formation of antibiotic-resistant bacteria can also be drawn. Increasingly radiation resistant forms may develop as the use of the technique is expanded (Robin). As yet, there have been no effective encounters of such mutated bacteria. But, concern about rogue mutant microorganisms has been discussed in recent developments in genetic engineering. Consumer organisations do not dismiss the possibility that mutant pathogenic microorganisms might result from low level of irradiation and believe that more research is required (Robin).

2.2.4 Sensory aspects

Numerous investigations on the effects of irradiation on taste show, that all foods undergo flavour changes. The majority of published work has concentrated on assessing the microbiological and organoleptic effects of irradiating individual food items. There is consequently considerable information on the dose levels that can be used beneficially on individual items without adverse organoleptic effects, but relatively little information on mixed food system in which individual items ideally require different optima of irradiation.

An area where there is still not a lot of experience is **In-prepared dishes** and **convenience foods**. For example, in a frozen chicken dish the effect of irradiation on the taste of the vegetables or the

sauce and which packaging materials might be affected by the treatment, particularly in the presence of different ingredients is not known (Campbell).
In a few investigations the effect of irradiation on the microbiological and organoleptic quality of a range of hot and cold meats was studied. These studies demonstrated that valuable effects could be achieved at low doses, but that further dose reduction would be desirable to avoid selection procedures in complex menues (Kilcast).

* Therefore like the studies on the nutritional quality of complex foods, the effects of irradiation on **sensory properties of mixed foods** should be more carefully investigated.

2.2.5 Combined treatment

More research on the **organoleptic qualities** and **microbiological safety** of foods irradiated in conjunction with **combined treatments** is demanded.

Organoleptic quality

In spite of the considerable research effort that has gone into the irradiation of food, relatively little is known regarding the implications of organoleptic changes in food to the consumer. Considering the effects of combination treatments, it is important to assess irradiation as a function of quality. This will be particularly important for the combination of irradiation with heat treatments and for the combination of irradiation with chemical treatment.
- For example, irradiation of mould in papayas requires doses of 2.5-6 kGy, which causes substantial damage to the fruit. Use of a 20 second hot water dip at 60 °C, however, reduces the necessary dose to 0.75 kGy. Under this combined treatment, it may be expected that the irradiation component would have minimal effect on organoleptic properties, whereas the heat treatment might produce some deterioration. Similary, the 0.7 kGy dose which is needed to disinfect can be reduced to 0.035 kGy by air heating at 40°C.

- Combination of low-dose irradiation with chemical preservation such as sodium chloride, sulphur dioxide or reduced pH has organoleptic implications, but changes other than flavour changes can also occur (e.g., colour loss in pork sausage (Kilcast). These effects were only investigated for individual processes, systematic research work is lacking in the literature.

Microbiological quality

Microbiological aspects of food irradiation combined with other treatments also need in-depth investigations.

- For example, for food treated with the combination irradiation/heat special concerns such as:
* the microbial history,
* the thermoradiation effects,
* the heat sensitivity of bacterial spores by irradiation

have to be taken into account.

- Further consideration arise in relation to the use of **chemical additives**. Irradiation could potentially be used in combination with conventional preservatives to reduce the use of these chemicals. Irradiation alone will not always serve to replace preservatives. For example, nitrite in bacon also maintains the colour of the product, but the quantity of nitrite required for the nonmicrobial effect might be less than that is required to control microbial growth. Combination treatments and the above effects have to be studied more in the future (Kilcast).

New combinated treatments

A very promising area for future development work is seen in the optimisation of the technique to permit treatment of products previously thought unsuitable. In the absence of oxygen, beef now can be irradiated under certain conditions. Ground beef is a microbiolocical high risk product, and any alleviation of the problem would be welcome. The recent incidences of ***Listeria*** in several countries has also revived interest in testing cheeses, particularly varieties made from raw milk.

2.3 Packaging aspects

In the field of packaging more exactly tested material for the concrete use in the irradiation technology is mainly required.

The passage of food through an irradiation facility generally requires previous packaging for convenient handling. The effects of ionising on the container material is therefore of considerable importance. It is not of over-riding importance, however, since food also undergoes a number of interactions with packaging material in absence of ionising radiation. The main reaction is the migration of additives present in the polymer into the foodstuff. Additives of concern include such non-polymeric substances as antioxidants, plasticisers and anti-fungal agents. In this perspective, it is of some concern whether irradiation influences known interactions or in any way induces new ones.

For the most part, the dose at which radiation effects become significant for the less radiation resistant materials - polypropylene, polyvinylchloride, cellulose, polyvinylidene chloride - is above 10 kGy.

* But in some manner the polymeric material, one of the major packaging type for food is affected by ionising radiation. The degree of chemical breakdown depends not only upon the type of polymers, but its physical state, environment and the incident dose rate.
It is obvious, therefore, that irradiation of food packaging requires careful consideration and choice of materials. At the moment currently available packaging materials are used for irradiated foods. It is likely that **development of packaging** materials **specically for irradiated food** products has to be accelerated if the method gains widespread acceptance. For example it has been noted by the US Department of Agriculture, that FDA approved materials are not currently employed in packaging meat and poultry products, and that further research and evaluation will be required before these products can be irradiated routinely.

* In relation with off flavours the effect of packaging also needs to be taken into account, especially when irradiation is being used in combination with **Modified-Atmosphere Packaging**. For example, irradiation of raspberries in-pack at doses as low as 1 or 2 kGy can produce fermented off-flavours typical of anaerobic respiration. This effect could be minimised by use of packaging materials with more suitable permeability characteristics.

* Research work has also shown that irradiation can potentially reduce migration of antioxidants from certain packaging materials into food. Similar work has shown, that flavour changes in food caused by certain packaging materials can be reduced or eliminated on irradiation, possibly by `locking.'

* Food packaging manufacturers will need knowledge regarding which packaging materials, adhesives and printing inks will be suitable for irradiation. This will necessitate testing programs.

2.4 Public education

To a larger extent compared to other food conservation processes the use of irradiation techniques depends strongly upon the actual and expected consumer behaviour. The subject of irradiated foods is an emotional issue with many consumers. The most striking reason is the broad **lack of information** and considerable misinformation which has been published which capitalises on the emotional fears of anything to do with radiation. Many consumers still have difficulties in the differentiation between Chernobyl and food irradiation technology. They are not aware that medical products irradiation technology, which is the same as food irradiation technology, has achieved fairly wide acceptance. Concerns relative to handling and disposal of the radioactive isotope such as Cobalt-60 must be also addressed.

On the other hand attitude studies have shown that the extent to which the public accepts or rejects irradiated food strongly depends on the presence or absence of the information that reaches the public. But the factual knowledge or good understanding of the irradiation process only comes to about 10% even in countries such as The Netherlands, where irradiated products have been on the market for 20 years.

Therefore most of the specialists indicate that much more consumer information is needed and the consumer must be provided with accurate, factual information to be communicated on a level which can easily be understood.

Various consumer organisations still have reservations towards irradiation of food. To guarantee maximum protection of consumer most consumer organisations demand extended efforts in the development of independent rigorous labelling of irradiated foods and further investigations of potential byproducts produced by irradiation of agrochemicals or plastic materials.

2.5 Detection of prior irradiation

The chemical composition of food is modified only very slightly by irradiation, and so any diagnostic techniques used to detect chemical changes induced in food components by prior irradiation must be necessarily be very sensitive. Previous research pointed out a number of promising detection methods for prior irradiation, but currently there is no accepted an universal method, which can be used for the detection of previous irradiation. Additionally the detection of irradiation, while possible in research, would be difficult to be integrated in industrial quality control systems.

Besides the specific research to improve the individual detection techniques there is a lack of:

* more data to guarantee a sufficient statistical reliability,
* an international comparison to prove the general application
* reference values.

Other factors which need more detailed research are the influence of:
* the moisture content,
* the storage conditions (relative humidity and temperature),
* the presence of oxygen,
* the contact of radiolytic product concentration and lifetime.

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3 Indication of research priorities

3.1 Reasons for irradiation

More investigative and research work has been carried out on food irradiation than on any other food preservative method. This development of food irradiation as a technique has been conducted under the direction of a number of major international organisations (e.g., FAO/WHO/IAEA). Results of this research in food irradiation around the world have indicated that irradiation of certain foods at low dose (defined as 10 kGy and below) may be the most technically and economically feasible application.
The following reasons reinforce a great interest in food irradiation.

* Increasing doubts exist in the public mind about the use of chemical additives as means of sprout inhibition, insect extermination and general food preservation. Even if these doubts frequently appear exaggerated upon serious reflection, irradiation is an alternative method which does not cause foreign residues in the food.
But the success of the irradiation technology in this area will depend to a high degree on the tolerating of applying inexpensive chemical additives.

* For world economic reasons the use of irradiation as a means for hygienization, especially to kill *salmonella* is important. Irradiation is mainly used for spices, dried vegetables, frozen shellfish, frozen chicken and egg products. Food borne diseases caused by bacteria such as *salmonella* are a serious problem with health, social and economic consequences in developing as well as in developed countries. In an advanced country such as Germany, in 1989, some 90,000 cases of infectious enteritis (most of them of foodborne origin) were officially reported. The real figure, however, is more likely to be somewhere between one and one and a half million cases (Käferstein). The increase of world trade in food and the risk of the foodborne illnesses have increased the uneasiness regarding to food safety in public health agencies. Recent studies show, that the irradiation process is an attractive method for the destruction of pathogenic organisms, especially in heat sensitive (deep frozen) food.

* Irradiation results for some food in a **shelflife extension** which cannot be obtained by chemical means or heat treatment. This is because chemical treatment does not penetrate into the interior of the food (e.g., fruits) or because a heat treatment cannot be applied without altering the character of the product (e.g., fresh fruit or vegetables). For fresh fruits and vegetables of ECC countries, the economic and sensory advantages justifying the additional costs must be proved.

* A special interest in irradiation exists in many tropical developing countries where **food losses** due to spoilage or to infestation of parasites (e.g., trichinella and toxoplasmosis) are extremely high and

where the economic conditions for building up a cool distribution chain from the producer to the consumer do not exist.

* Finally, irradiation has a wide technological **application on the medical and pharmaceutical industry**. For example, surgical sutures have been sterilized only by irradiation for many years. Animals used for testing new medicines and food additives have been the subject of feeding studies with irradiated foods for many years.

The reason for this successful use of irradiation technology is the great advantage over the previously usual chemical disinfection. That is, irradiation can be carried out in a sealed package, thus preventing reinfection with certainty. Irradiation also has the advantage over heat treatment that heat sensitive material can be treated.

Another advantage of the radiation process is flexibility. Irradiation can be employed to preserve a variety of foods in a range of size and shapes - crates of potatoes, flour in 50-100 pound sacks, even meat, fish or poultry sandwiches. The product can be packed dry in larger containers with better portion control.

In spite of these prospective uses, several problems still exist as barriers to early commercialization of the radiation process:

- government regulation
- industry interest in the economic feasibility
- international trade agreements
- consumer acceptance of irradiated foods.

Worldwide an implication of the commercialisation of food irradiation will be predicted by economic experts in view of the increase in the world's food supply. However the share of irradiated food in the EEC is estimated not over 1% until 2000 and even optimistic predictions do not estimate more than 5% after 2000 (Diehl). It must be emphasized that a licence for irradiation of special food (e.g., spices) does not mean that all the food will be irradiated. The expenses for irradiation can only be offset if there is a need (e.g.,microbiological contaminated spices). Similar to the irradiation of potatoes and onions only those which will be stored for a long time would require irradiation.

Also irradiation cannot be used for every item, as it alters the taste or appearance of some foods. But, this is not different from other forms of processing (e.g., deep freezing of tomatoes or sterilizing of milk).

Future Research Priorities

In view of the many results from studies already conducted future research priorities should be put in those fields which are of long term interest for the industry, consumer as well as for the governments regarding above stated economic, social and health views. However irradiation technology should be improved via new basic research like other preservation methods. Especially because future economic gain is difficult to predict at present time. Another reason is that the profitability of irradiation is strongly dependent on the economics of scale and the expense of other food processing methods (e.g., cheaper chemicals) in the future.

For particular areas the following research priorities can be explored to increase the existing knowledge about the effects of food irradiation and to facilitate future evaluation.

3.2 Priority in irradiation process and facilities

As mentioned above, food irradiation with radiation sources is already an industrial application. In future, however, the **use of electron beam irradiators** is foreseen for various reasons. As the available radioactive material becomes rare the cost will rise and since the public does not oppose the use of electron beam irradiators as it does oppose the use of radiation sources the use of electron beam irradiators may be more desirable. Further, according to FAO up to 40% of the harvest of cereals grains are lost and one main reason is insect damage. Most of these insects could be completely eliminated by radiation doses as low as 0.2 kGy. The main advantage for use of electron accelerators for radiation of grain is the high and adjustable beam power which allows for a flow of bulk material at high velocities. At lower electron energies, approximately up to 1.5 MeV, robust and economic accelerators are available.
Therefore the need for the necessary basic results for a practical application is particularly stressed for

* the homogeneity of dose distribution
* the interaction into the handling system
* reproducible results.

3.3 Priority in dosimetry

All irradiation of food relies on some form of dose and effect relationship. Since measuring such effects are not generally practical as a means of process control, dosimetry is the only independent method that can guarantee the quality of the process. Dosimetry thus forms the basis for documentation, fulfilling the legal, regulatory and technological requirements of the food irradiation process. With increasing harmonization of laws in the EEC, the control of radiation doses becomes important within the EEC and in those countries where irradiation is presently still not allowed.

The amount of irradiation absorbed by food within a defined area is determined by many factors. At the present stage of development, dosimetry can only serve adequately within certain limits.

Therefore, more research is needed to improve the existing measurement systems. In detail the following research areas are assessed as important:

* The development of dosimeters, especially to cover the range of 0.1 kGy - 5 kGy;
* The effects of external influences on dosimeter response, such as low or high temperature (-40°C- +60°C);
* The development of primary standards relevant to high-dose photon and electron calibrations;
* the development of more dosimeters suitable to measure electron beam doses, especially in processed free-flowing particulate food and bulk solids.

3.4 Priority in wholesomeness aspects

The evaluation of the wholesomeness of irradiated food is based on a large body of scientific data from the main areas: the radiolytical effects of ionising radiation, the toxicity of irradiated food, the microbiological effects and the nutritional aspects. The research supports the conclusion that the irradiation of food up to 10 kGy results in wholesome food for all investigated foods.

The areas which the research should be continued are mainly cited as follows:

- nutritional and toxicological investigations at doses over 10 kGy,
- radiolytical investigations to expand the toxicological studies,
- nutritional, sensory and microbiological research in combined processes.

3.4.1 Research in the dose range above 10 kGy

In the range above 10 kGy data from radiation chemistry, nutritional, and microbiological aspects of food should be expanded.

The commercial use of the irradiation is seen mainly in the range of doses below 10 kGy at present time. The reasons for that are mainly the costs of irradiation, which increase with dose and secondly the appearance of unwelcome side effects which turn up with increasing doses. For sterilizing (destruction of all microorganisms in food) a radiation dose of 30 kGy or larger is necessary. This high dose causes changes of taste, smell, and consistency in most foods. To prevent this, special conditions must be made (e.g., irradiation in a frozen state) and result in additional expenses. It is therefore not very likely that sterilizing by means of irradiation will be used on a wide range of foods. However, in special cases like the production of sterile diets, food for expeditions, and food for astronauts, an increasing demand is foreseen. British and American hospitals have used already such sterile diets for years to serve sensitive patients.

Therefore data of effects of irradiation in the "high dose range" should be worked out.

3.4.2 Priority in toxicological aspects

In spite of the statement of the Joint FAO/WHO Expert Committee that irradiated foods are not injurious to health and that further toxicological studies are not necessary, consumer organisations cite that there has been insufficient research to indicate whether subtle long term effects will occur. Sometimes the argument is heard, that there is no final proof up to now concerning the existing of toxic or mutagenic substances formed by irradiation.
Since animal feed studies are very expensive and the result of animal feeding trial cannot necessarily be transferred directly to humans new concepts for assessing the wholesomeness of irradiated foods were developed such as radiochemical investigations and short-time mutagenicity screening tests.

In the interest of the consumers many scientists think it is important
* to continue the collection of radiolytic byproducts,
* to continue the investigations about the chemistry of radiolytic byproducts,
* to understand the interactions of radiolytic byproducts in the food matrix and their biological properties.

Research priorities should therefore comprise
* the developments of methods for detection and identification of radiolytic byproducts,
* particularly for new types of product groups,
* in the dose range above 10 kGy,
* for the formation of radiolytic products from contaminants such as agrochemicals.

3.4.3 Priorities in combined processes
Nutritional, sensory and microbiological aspects

A further field of research may be seen for irradiation in combination with other food processes (e.g., irradiation combined with heating or chemical preservatives) as well as in combined products (prepared dishes and convenience food). It was concluded that the use of combination treatments could provide the consumers and food industry with convenient and cost-effective treatments and that product safety and the supplies of nutrients could be improved by such treatments.

In the field of combined processes, it is recognized that more research data are required to be able to predict effectively food microbiological safety, product stability, nutritional status for different combination treatments. For example, some studies tend to show that less destruction occurs when nutrients are irradiated in the complex foods actually consumed than that which occurs when the same nutrients are irradiated in a model system.
For the destruction of microorganisms a lot of synergistic effects have been found for radiation when applied in combination with other factors such as heat. On the other hand, microorganisms are more protected against the effect of radiation by complex substrates such as protein rich commodities.

In detail the following types of research are indicated as necessary to increase the existing knowledge:

* Studies on the mechanism of combined effects of irradiation with other treatments with particular emphasis on synergistic interactions:
- sensory and nutritional effects,
- microbiological aspects like thermoradiation effects, influence of microbiological load, changes in microbiological flora,
- effects of reduced chemical preservation.

* A comparative analysis of the benefits of integrating irradiation with other food processes to demonstrate improved safety, nutritional and economics of food processing, for single and complex foods.

* The potential of combined treatments should also be explored for products previously thought unsuitable (e.g., currently high risk products like liquid-egg products, ground beef, corned beef briskets or pork sausage) in relation to extend their shelf-life, or for large pieces of proteinaceous foods in aseptic packing. Some authorities argue that the suggestion HTST technique should be developed in line with a simultaneous electron beam irradiator, points in the right direction for the future (Farkas).

* Energy and cost-benefit analyses in relation to storage, distribution and home preparation of combined shelf-stable or chilled products should be performed, preferably in comparison with alternative and established technology.

* A relative small area of research is the use of irradiation combined with other treatments to improve physical and technological properties of food. Some need for further research is seen for some special effects (e.g., to tenderize protein of tough texture, to inactivate certain enzymes or to improve the digestibility of straw).

3.4.4 Priorities in microbiological safety aspects

In view to the harmonization of the common market it can be expected that irradiated products will be available in the whole EC-market in a foreseeable future. The microbiological safety achieved by food irradiation process is fully comparable with that of other currently accepted food treatments. As with other preservation techniques, problems will arise due to the resistance of particular microorganisms to irradiation. Research results have shown that microbiological safety evaluation of a specific irradiated food can be based only on studies that have specifically been designed to reflect all the circumstances encountered in commercial irradiation, the hygienic aspect of each individual commodity and the post-irradiation storage conditions.

Since food irradiation is a form of food preservation with its own particular advantages and limits, it is necessary as in other preservation processes to establish microbiological criteria for Good Manufacturing Practice (GMP). Still there exist some lack and difficulties in establishing reference values for a microbiological quality assurance before and after the irradiation process.

Future research should therefore address the problem areas

* dose requirement as a function of microbial load,
* selection of spoilage organisms or development of mutated bacteria,
* storage and packing conditions,

to guarantee the microbiological safety of irradiated food in the complete process.

* Mathematical modelling for predicting food safety and spoilage for irradiated products would be necessary for long term objectives.

3.5 Priorities in packaging aspects

One great advantage of the irradiation process is that recontamination of foods can be excluded because the product can be treated in the package.

But also for the separate treatment of packaging material a wide range of application is foreseen. For example, from the standpoint of cost-effectiveness one of the most promising applications of in-line electron sterilizer is for aseptic packaging (Nablo).

For electron beam sterilization of food packaging three basic areas of application are seen:

1. Nonaseptic or substerilization materials or package structures are sanitized or sterilized for later product packaging. In this scenario the package web roll would be sterilized for form/fill/seal or pouch/thermoformed container application.
2. A second area would be an aseptic operation in which a performed container and/or its closure or a formed-inline package would be sterilized for aseptic filling.

3. A third area involves use of electron beams for sterilization of sealed overwraps of already sterilized and packaged products (Nablo).

The suitability of packaging material for irradiation therefore is of considerable importance. All packaging polymeric materials are affected by ionising radiation. Analysis of polymers showed that the polymeric packaging has been found resistant to doses of 10 kGy. But the resistance is influenced by the presence of oxygen. Many polymers such as polyethylene rapidly undergo oxidative degradation and a wide range of oxygenated compounds can be formed from irradiation which can migrate in the food or can lead to decrease in mechanical properties. Therefore, more fundamental information about migration from irradiated packaging material is needed (McGuinness).
It is obvious, that irradiation of food packaging requires careful consideration and choice of material.

For the proper use of packaging food, manufacturers will **need more approved packaging materials**, which are tested with respect to the following criteria:
* The polymer must survive irradiation and subsequent storage without loss of vital properties such as mechanical strength and optical transmission. In the case of the former, tensile, burst and tear strength may be quantified.
* The material will neither transfer hazardous materials to the food nor generate chemical substances which will adversely affect organoleptic properties upon irradiation.
* Retention of seal strength after irradiation of polymers used in lidding and pouches containers.
* Retention of barrier properties in packaging polymers used for controlled atmosphere containers after irradiation.

3.6 Priorities in public information

In the final analysis, for food irradiation to become widely applied, it must be accepted by the consumer. It is obvious that the success or failure will ultimately depend upon consumer acceptance or rejection of the process. This, in turn, will influence also the future research priorities, because scientists, technologists and equipment manufacturers alone do not make a successful process. Perhaps the most striking impediment is the broad lack of information, and even the prevalence of considerable misinformation, of a part of the public. Some consider the consumer misinformation such a big problem, "that unless the food irradiation industry comes to terms with this it may well have wasted four decades of research and developing work" (Taylor).
At the moment consumer reactions, when expressed, have tended to be hostile. But in a research paper of the consumer reaction in the USA explored changing public reactions towards the process, the degree of acceptance was found to increase with degree of information provided. The authors

noted that this was in line with a strong correlation between approval of irradiation and level of information on the nature and purpose of the process.
The methods used to communicate the positive benefits of the irradiation technology are regarded as unsufficient by specialists.
To ensure marketplace acceptance and utilisation modern marketing concepts are needed.

* Information on food irradiation on the different aspects of food irradiation (i.e., foodborne diseases, safety and nutrient, food loss, and food trade) should be distributed to professional organisations and consumer.

* In view of the consumer organisations claims extented investigations should be supplemented in order to show the (non) harmfullness of byproducts.

* The demonstration of economic feasibility and benefits also has to be made clear to the food industry as well as impact of the health aspects of irradiated foods emphasized to the governments.

The best way to convince the public, however, would be to make those irradiated foods proven to be safe, available and allow them to decide for themselves. Experience elsewhere has shown that once the quality of these irradiated foods is appreciated, the technique is more readily accepted (Kilcast).

3.7 Priorities in detection methods for prior irradiation

The existance of sufficient detection possibilities of prior irradiation is of some considerable importance because it raises the possibility that irradiated food items could be recognized, be traded and consumed regarding to the regulations which govern whether particular foods can be irradiated. Given the present level of public sensitivity over radiation-related topics the introduction of the irradiation technology without adequate means of monitoring its effects leave the advocates of the technique open to criticism.

In the last years, extensive research led to some promising detection methods such as thermoluminescense and electron spin resonance techniques to estimate prior irradiation in inorganic materials (herbs, minerals or bones). These techniques are used as routine methods.
* Priorities for these **established methods** are particularly the development of international standards and the application in industrial and official quality control situation.

Other promising methods are still **exploratory techniques** which need more research such as DNA based methods or some physical methods like the electrical impedance technique. Because these approaches hold considerable diagnostic promise, more detailed research and the need

* to work out the application limits is required to make possible a wide use for these methods.

For other suitable methods like the microbiological **epifluorescence filter technique** method particular effects of secondary processing such as heat treatment and cooking have to be investigated more in detail.

More and more sensitive analyses methods are the key to future work improvements, such as the development of **antibodies of macro-molecules** damaged by irradiation or the use of radioactive tracers to detect carbonyl compounds.

Research potential **for all methods** is seen in areas such as

* determining the storage conditions or the application of combined processes,
* the collection of statistical data (e.g., in national and international ring tests),
* the development of robust and reliable techniques, which are capable, ultimately, of standardisation and development by semi-skilled personnel.

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4 Summary

The objectives of the study are to summarize the **actual state of the art** of the research activities about food irradiation with special consideration of newer studies since 1985 and to indicate the **remaining knowledge gaps** and resulting **research priorities**.

State of the Art

The **irradiation process** (Co 60) has proved to be very successful on wide range of medical implements and food products and has become commercial routine practice in a number of countries. In a lot of current studies, systems for the practical **measurement** of the **absorbed dose** are improved.

An **actual need of radiation technology** is seen in the field of application where other alternative methods are either restricted, contested or not present: replacement of chemical treatment (inhibition of sprouting, insect disinfestation, decontamination of foods); improvement of microbiological safety (elimination of pathogenic bacteria like salmonella and parasites); improvement of quality and availability of tropical fruit products.

On the area of **wholesomeness aspects** extensive literature supports the conclusion that radiation treatment with licensed doses guarantees the nutritional and toxicological safety of irradiated foods. The present **microbiological** literature reaffirms the basic conclusions of earlier literature, that microbiological safety of irradiated food is fully comparable with that of food preserved by other preservation methods.

The use of **irradiation in combination with other treatments** (heat treatment, Modified Atmosphere Packaging (MPA), irradiation at cryogenic temperatures, chemical treatment) is seen as one of the most effective ways of using irradiation.

The average dose at which radiation effects becomes significant for **packaging material** (e.g. polypropylene, polyvenylchloride, cellulose) is mostly < 10 kGy. An exact approvement for the use in food irradiation is at present only done for single layer films, not for polymers.

At present 19 out of 36 irradiation permitting countries actually **conduct commercial irradiation**, among them the EC-members Netherlands, Belgium and France. The total commercial market is now some 500,000 tonnes per annum and includes mainly sprout inhibition (potatoes, onions), disinfestation (spices, seasonings, cereals), decontamination and shelf life extension (tropical fruits, meat, fish and poultry products).

The estimated **costs** for the different fields of food irradiation vary for the low dosis range between about 0.03 - 3 US cents/kg, for the middle dosis range between about 0,03-7 US cents/kg and for the high dosis range between 2-20 US cents/kg.

National **legislation** and regulation of **labelling** on food irradiation within the EC varies considerably and food irradiation is accepted only by about one half of the EC members.

Reactions of the consumer to food irradiation are tended to be hostile, mostly due to a lack of information or misinformation. In studies it was found that there is strong correlation between approval of food irradiation and the degree of the consumer education.

Intensive research led to a number of **detection methods** of irradiation. Some techniques such as thermoluminescence and electron spin resonance technique for the estimation of irradiation in inorganic materials, are partly applied as routine method. Other promising methods such as the epifluorescence filter technique, electrical impedance method or DNA based methods are currently tested or developed for the practical use.

Remaining knowledge gaps and research priorities

On food irradiation more investigation and research work has been carried out than on any other preservation process. In the literature following **remaining knowledge gaps** and resulting **future research priorities** are cited:

* In the area of the **irradiation process and facilities** more research work should be spent on the use of electron accelerators e.g. for the irradiation of free-flowing bulk quantities, like grain.
* For the routine **measurement of the absorbed dose** further improvements of the determination of the radiation dose are necessary (dosimetry in electron beam accelerators, testing of effects of external influences, development of reliable types of dosimeters and measuring systems).

* In the area of **nutritional aspects** some lack of information on nutritional changes of "complex" foods in the **dose range over 10 kGy** are seen.
* Further **toxicological investigations** should comprize the developments of methods for the detection of radiolytic products (identification of radiolytic products and interactions in new types of products, the formation of radiolytic products from contaminants such as agrochemicals).

More **microbiological** research work is necessary which reflects all circumstances encountered in commercial irradiation processes, to work out microbiological criteria for Good Manufacturing Practice (GMP) and acquire reference values for microbiological quality assurance.

* In the field of **combined processes** it is recognized that more research data are required to be able to predict food microbiological, sensory and nutritional quality for different combined treatments. A further area of future development work is seen in the optimisation of combined techniques to permit treatment of products previously thought unsuitable (e.g. elimination of Listeria in raw milk or the extension of shelf-life of high risk products like liquid egg-products or ground beef).

* For all possible changes of **packaging material** food manufacturers will need knowledge which packaging materials, adhesives and printing inks will be suitable for irradiation.

* Most of the specialists indicate, that much more **consumer education** is needed and the consumer must be provided with accurate, factual information based on a level which can be easily understood.

* In the field of **detection methods** priorities are the development of international standards and the application in practical quality control situation for methods such as thermoluminescense and electron spin resonance techniques (partly routine methods). Other promising methods like the epifluorenscence filter technique method, DNA based methods or electrical impendance technique need specific research to be improved.

European Commission

EUR 15017 – Research priorities relating to food irradiation

A. Fink, D. Rehmann

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The objectives of the study are to summarize the actual state of the art of the research activities about food irradiation with special consideration of newer studies since 1985 and to indicate the remaining knowledge gaps and resulting research priorities.

The irradiation process has proved to be successful on a wide range of medical and food products and has become commercial routine practice in a number of countries.

An actual need for radiation technology is seen in the field of application where other alternative methods are either restricted, contested or not present: replacement of chemical treatments, improvement of microbiological safety in certain cases, quality and availability of certain tropical fruits.

The study reports on various technical aspects related to wholesomeness, microbiology and packaging materials.

The use of irradiation in combination with other treatments is seen as one of the most effective ways of using irradiation.

At present 19 out of 36 countries that permit irradiation conduct commercial irradiation. The total commercial market is now some 500 000 tonnes per annum.

The reaction of the consumer to food irradiation still tends to be critical. Studies suggest that there is a positive correlation between approval of food irradiation and the level of consumer education.

Intensive research has led to a number of detection methods which can demonstrate whether foods are irradiated or not. Some techniques are or can be applied. Other are currently tested or developed for practical use.

The study lists a number of remaining knowledge gaps and research priorities in the areas of the irradiation process and facilities, nutritional aspects, toxicology, combined processes, packaging and detection methods. It is recommended that more consumer education is needed and that the consumer must be provided with accurate, factual information which can be easily understood.

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