Food Irradiation

A Reference Guide

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Foreword

The multidisciplinary nature of food irradiation, involving branches of science such as microbiology, chemistry, physics and nuclear technology, toxicology and nutrition, has made food irradiation into a complex issue even to specialists in any of these disciplines. In addition to these sciences are the disciplines related to regulatory aspects, economics, marketing and consumer science. In short, there is no known food technology which is more studied but less understood than food irradiation.

The lack of understanding of the safety, benefits and limitations of food irradiation has led several advocacy groups to oppose the introduction of this technology in the past few decades. These groups often inspire the fear of the public concerning 'unknown' risks of anything associated with nuclear technology. The apprehension web has put food irradiation on the defence almost from the start. However, after decades of research on the various aspects mentioned above, food irradiation has emerged not only as a safe technology but it is beginning to demonstrate its effectiveness as a method of food processing/preservation for a wide variety of foods and in increasing numbers of countries.

There are a number of issues which have propelled food irradiation to the centre stage of food processing/preservation along with several other technologies. Among these issues are the increasing public awareness of the risks of food-borne diseases, especially from food of animal origin; the increasing restrictions and prohibitions on the use of a number of chemicals in food, especially fumigants; the risks from increasing global trade in certain food which harbour pests and diseases; and the increasing need for food for the fast growing population in developing countries. The technology has been approved by some 40 countries to date and some 30 countries are using it, on a varying scale, for treating food for commercial purposes.

This reference guide is an ABC on food irradiation on the one hand and an encyclopedia of food irradiation on the other. The authors have painstakingly compiled all terminologies related to this technology and have listed items ranging from '*Aeromonas*' to '*Yersinia*' for microbiological aspects; from 'Apple' to 'Poultry' to 'Wheat' which can benefit from irradiation; vitamins in food which may be affected by irradiation; regulatory aspects including various methods of detection of irradiated food; consumer acceptance and commercial applications to date, etc. With its uniform format and full references throughout, the reference guide is most valuable to policy makers in governments, the food industry, research institutions, academia, and trade and consumer organizations. No library will be complete without this book.

The road to commercial application of food irradiation must not be paved by misunderstanding and emotion but by scientific evidence, co-operation and understanding by all concerned. This reference guide will contribute to a better understanding of the complex issues of food irradiation. With the growing interest in the application of food irradiation in many countries, the publication of this book is not only most timely but urgently needed to provide the food industry and consumers with accurate information on this safe and highly effective technology to combat food problems in this demanding world.

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Preface

This reference guide is intended for anyone who requires a source book on food irradiation, including those in the manufacturing and retail industries, and teachers and students in academia. The extent of the information covering food irradiation is impressive but it is scattered throughout a vast literature. Our aim is to provide basic information about the major aspects of food irradiation and also to simplify access to the more detailed information that is available. The use of an alphabetical format with cross referencing facilitates access to information on the many aspects of food irradiation, including microbiology, food products, safety, nutrition, toxicology, detection methods and legislation.

With such a wide range of sciences within the field of food irradiation, the authors felt a real need for help with some aspects of the topic. In this regard we would like to express our thanks to Dr David Kilcast, Leatherhead Food RA, UK, and to Dr John Woolston, Isotron, UK, for scrutinizing key parts of the text and for making valuable suggestions for improvement. Particular thanks go to Dr Paisan Loaharanu, Joint FAO/IAEA Division for Nuclear Techniques in Food and Agriculture, for his help and comments, and for contributing the Foreword to this volume. For help in obtaining literature on food irradiation, we are indebted to the Leatherhead Food RA for permission to use library resources, and to the staff of the Library and the Scientific and Technical Information Department. In addition, we would like to thank Allison Ross, MeV industrie S.A., France, and Michelle Marcotte, Nordian International Inc., Canada, for information and illustrations, and Dr Mike Wilkinson for his computing expertise.

We hope that this guide will assist those who are interested in realizing the potential of food irradiation as an effective, safe and accepted food preservation method.

Vanessa M. Wilkinson
Grahame W. Gould

How to use the reference guide

Key aspects relating to food irradiation are listed alphabetically. A full list of entries can be found at the end of the book, headings are also classified into: Main headings, Biological, Detection methods, Food components, Food products, Microbiological, Physical and Toxicological.

The Introduction gives an overview of the role of food irradiation amongst the range of currently applied and 'emerging' food preservation technologies. Each entry in the reference guide aims to summarize salient work on the subject and provide key reference. Radiation doses are quoted in kilograys (kGy). Cross-referencing to relevant sections in the book is highlighted using *italics* within the text and a *see also* list.

Introduction

Trends in food spoilage and safety

Foods deteriorate as a result of physical and chemical changes, the activities of enzymes and of micro-organisms (Table I). In addition, post-harvest losses occur due to insect pests. The activities of micro-organisms are by far the most important quantitatively, leading to enormous levels of spoilage (Table II). Losses of commodity foods, particularly in the less-well-developed countries of the world, are estimated to exceed 50% for fruits and vegetables and 10% for cereal grains and legumes (Anon, 1993). Deterioration in colour, taste and texture of foods is catalyzed by endogenous enzymes, and undesirable physiological changes, such as ripening and sprouting, degrade food quality.

The presence of certain micro-organisms in foods may lead to food poisoning by infection or, if the micro-organisms have multiplied in a food, to intoxication, in some instances (Table II). Unfortunately, in many developed countries, despite public awareness of food poisoning risks, the numbers of food poisoning cases are rising, rather than falling, year by year (e.g. reported cases of disease caused by *Salmonella* and *Campylobacter* approximately doubled between 1983 and 1993, in the UK, with substantial economic consequences (Roberts and Sockett, 1994)). In developing countries, food poisoning remains one of the major causes of morbidity and mortality. Control measures are evidently failing or, at least, not making the progress that we should expect in the final decade of this millennium. New approaches to the effective elimination of the most important of the food poisoning micro-organisms from the relatively small number of most frequently contaminated foods are urgently needed.

Food preservation technologies

The major food preservation technologies, which are employed to counteract the deleterious effects of micro-organisms in foods, mostly act by inhibiting or delaying their growth rather than by inactivating them (Table III). For example, the use of cold, low pH, salts, sugars, preservatives, etc., all act essentially by inhibition. Many

Table I Quality loss reactions of foods (adapted from Gould, 1989).

Physical	Chemical	Enzymic	Microbiological
Mass transfer, movement of low MW components	Oxidative rancidity	Lipolytic rancidity	Multiplication of spoilage micro-organisms
Drying, loss of succulence, caking	Loss of colour	Proteolysis and other enzyme activities	Presence of infectious micro-organisms
Hydration, loss of crisp textures	Non-enzymic browning	Enzymic browning	Multiplication of toxinogenic micro-organisms
Loss of flavours	Loss of nutrients		
Freeze-induced damage			

Table II Microbial food spoilage and food poisoning problems (adapted from Gould, 1989).

Problems	Examples
Food spoilage	
Excretion of major metabolic products	Lactic and acetic acids causing souring; gases (carbon dioxide, hydrogen) causing blowing.
Excretion of minor metabolic products	Low odour threshold compounds (amines, esters, thiols) causing off-odours, discolouration.
Secretion of enzymes	Lipases, proteases, cellulases, etc., causing flavour and texture changes.
Biomass	Visible presence of micro-organisms (slime, haze, mould colonies, etc.)
Food poisoning	
Presence of infectious micro-organisms	*Salmonella, Campylobacter, Listeria.*
Multiplication of toxinogenic micro-organisms	*Staphylococcus aureus, Clostridium botulinum.*

of the new developments, which have come into use or have been proposed in recent years in reaction to consumers' requirements for less severely processed, more natural, additive-free foods, also act by inhibition (e.g. 'modified atmosphere packaging', use of naturally-occurring antimicrobials; Dillon and Board, 1994).

Since the major underlying cause of microbial food spoilage and food poisoning is ultimately the presence of the micro-organisms in the foods in the first place, it follows that inactivation techniques are ideally preferable to inhibitory ones. Heat is the only food preservation technique, which is used on a large scale, that acts primarily by inactivation.

A problem with inactivation techniques, such as high-temperature processing, has been that they often tend to produce unacceptable damage in the quality of food products. For this reason, procedures that minimize heat-induced damage are being pursued, e.g. rotary retorting, microwave heating, ohmic heating, etc., for pasteurization and sterilization. Also, essentially non-thermal techniques are being explored and some are already being exploited on a small scale, e.g. enzymic techniques such as the addition of lysozyme, other enzymes and naturally-occurring antimicrobials to foods; physical techniques such as the application of ultra-high pressure, high-voltage electric discharges ('electroporation'), ultrasonics combined with mild heat and slightly raised pressure ('manothermosonication') (Table III, Gould, 1995).

These 'emerging' techniques are novel and scientifically challenging but few of them are widely employed. As yet, one of the most effective alternatives to heat for the inactivation of micro-organisms is ionizing radiation.

Table III Food preservation techniques (updated from Gould, 1989).

Mode of action	Preservation technique
Inhibition or slowing of growth	Lowered temperature by chilling, freezing.
	Reduced water activity achieved by drying, curing with added salts, conserving with added sugars.
	Restricted availability of nutrients in water-in-oil emulsions.
	Removal of oxygen from vacuum packs.
	Increased carbon dioxide, in 'modified atmosphere' packs.
	Addition of acids, directly or by fermentation.
	Increased ethanol levels by fermentation, fortification, release in packs from sachets.
	Addition of preservatives including naturally-occurring antimicrobials.
Inactivation	Heat, to blanch, pasteurize or sterilize, by hot air, water or high-pressure steam; by newer methods including microwaves and electrical (ohmic) methods.
	Ionizing radiation to inactivate pathogenic or spoilage micro-organisms in foods.
	Ultraviolet radiation to inactivate micro-organisms in water or on the surfaces of foods and packaging materials.
	High-intensity visible laser and non-coherent light to inactivate micro-organisms in water and on surfaces.
	Application of ultra-high pressure.
	Application of high-voltage electric discharges.
	Application of ultrasound with mild heat and pressure (manothermosonication).
	Addition of bacteriolytic (e.g. lysozyme) and other enzymes and natural antimicrobials.
	Acid dips and sprays for carcase decontamination.

Ionizing radiation

Food irradiation is the use of ionizing radiation to increase food storage life, reduce post-harvest food losses and eliminate food poisoning micro-organisms. The effectiveness of ionizing radiation, its penetrating power and its straightforward kinetics make it much simpler, in practice, to use than heat. It does bring about serious organoleptic changes in some foods, but very little change in others. In this respect, it is analogous to most of the other means of food preservation that alter the quality attributes of different foods to some extent.

The toxicological aspects of food irradiation have been studied more extensively than for any other food preservation technique. As a result of these studies, the toxicological safety and 'wholesomeness' of foods, irradiated up to specified doses, have been judged to be satisfactory and to introduce no special or nutritional problems (WHO, 1981). This has led to acceptance by 130 governments of a Codex General Standard for Irradiated Foods (Codex Alimentarius Commission, 1984) and to approval by 37 countries of over 40 foods or groups of foods for consumption. Currently, full-scale implementation is inhibited by issues concerning economic viability and the levels of consumer acceptance of the process (Lagunas-Solar, 1995).

Conclusions

Substantial advances have been made in understanding the basis of efficacy of food irradiation for the reduction of food spoilage and for the improvement in food safety. However, although a surge in application was expected, the expansion in the use of food irradiation has been slow. Without doubt, a major reason for this has been the reluctance by consumers in many countries to accept that the process is satisfactorily safe, in spite of the extensive scientific evidence that now exists.

New inactivation techniques are urgently needed to safely supplement the use of heat, and other more severe preservation procedures, for the improvement of food quality and safety. New techniques to extend the storage life of commodity foods are necessary in order to reduce the extensive losses that now occur. Food irradiation could fulfil these requirements for some foods if wider understanding and acceptance of the treatment could be achieved.

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A

Additives
Irradiation allows the reduction or elimination of certain food additives by replacing their functions or by making their use unnecessary (Loaharanu and Urbain, 1982), e.g. preservatives that are used to prevent or delay the growth of *micro-organisms* in foods (e.g. sorbate, benzoate, propionate, sulphite, *nitrite*, etc.).

Certain additives, in particular those that act as antioxidants, may be of value in some irradiated foods. Their function is to reduce radiolytic effects that may potentiate undesirable changes, e.g. in *flavour*, odour and *colour*. In particular, *ascorbic acid* and its derivatives have been reported to improve the organoleptic quality of irradiated cured *meat* products (Proctor *et al.*, 1956), *fish* and *fruit* products (Huber *et al.*, 1956).

There have been concerns that irradiation of foods that contain additives may pose a health hazard. The FDA has investigated the effects of irradiation on foods containing additives, e.g. colouring agents and preservatives, comprising 0.01–1% of the total food weight. A radiation dose of 10 kGy yielded *radiolytic products* of the order of 3–30 parts per billion. This is considered to be a negligible amount in the diet, thus the probability of harm is extremely low (ICGFI, 1991).

See also Sensitizers.

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Adenovirus *see* Viruses.

Aeromonas

General
Although *Vibrio* species are well known agents of food- and water-borne illness, members of other genera, originally within the Vibrionaceae, *Aeromonas* and *Plesiomonas*, have been implicated as well.
Aeromonas hydrophila, a facultatively anaerobic Gram-negative, comma-shaped bacterium, is considered to be an important food poisoning organism. It is widely distributed in fresh and brackish waters, and may often be isolated from the faeces of healthy humans.

Radiation resistance
Aeromonas hydrophila is much more radiation sensitive than the salmonellae and would therefore be adequately controlled by radiation doses targeting these organisms. For example, Palumbo *et al.* (1986) found the *D-value* for *A. hydrophila*, γ-irradiated at 2°C in ground uncooked *beef*, to be about 0.14 kGy. In buffers, media and in *fish*, *D-values* ranged from about 0.13–0.20 kGy, varying with the strain, and up to 0.34 kGy, in *fish* irradiated at –15°C (Palumbo *et al.* 1985).

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Aflatoxin *see* Moulds.

Albumen *see* Eggs.

Alginate

Solution viscosity and gel strength of sodium alginate decreases, with increasing radiation dose, up to 10 kGy. Providing these changes are taken into consideration, irradiation may be a useful means of microbial decontamination of sodium alginate (King, 1994). With increasing radiation dose, a decrease in molecular weight is observed. The use of irradiation to produce lower molecular weight species of alginates, with known properties, may be of interest.

See also Gelling agents.

Reference

King, K. (1994) Changes in the functional properties and molecular weight of sodium alginate following gamma radiation, *Food Hydrocolloids*, **8**(2), 83–96.

Almond *see* Nuts.

Alternaria *see* Moulds.

Ames test

The Ames test has been used in toxicological studies of irradiated food. The test is designed to detect *mutagens* by exposing *micro-organisms*, which have well-defined genetic 'markers' in their chromosomes, to suspect substances (e.g. irradiated materials, additives, contaminants). Mutagenicity is indicated by changes in the well-defined genotype of the micro-organism (e.g. *Salmonella typhimurium*, Ames *et al.*, 1975). The relevance of the test to human carcinogenicity is improved by incubating the suspect substances and the detector-micro-organisms together in the presence of human tissue, in particular, microsome preparations derived from liver. In this way, any breakdown products produced by metabolism of the substances, and which may be mutagenic, are screened by the test as well.

See also Formaldehyde; Toxicology.

Reference

Ames, B.N., McCann, J. and Yamasaki, E. (1975) Methods for detecting carcinogens and mutagens with *Salmonella*/mammalian-microsome mutagenicity test, *Mutation Research*, **31**, 347–54.

Amino acids *see* Proteins.

Animal diets

Concerns about the *wholesomeness* of irradiated food have resulted in numerous animal feeding trials of radiation-sterilized diets. Specific feeding trials involving multigeneration studies of mice, rats and pigs have been undertaken, with numbers of animals studied ranging up to over half a million. Furthermore, breeding and performance studies of poultry and pigs given feed, irradiated at doses below 10 kGy, to eliminate salmonellae, showed no adverse effects. The observations supported the general conclusions that there were no reasons to expect toxicological problems from the ingestion of irradiated foods (WHO, 1981).

The use of irradiation to destroy *micro-organisms* in diets of laboratory animals, animal feed and pet food has been reviewed by CAST (1989). There is widespread commercial use of doses, up to 45 kGy, to sterilize diets for laboratory animals. The nutritional quality of the feed is maintained, products are acceptable to the animals, and there are no toxic residues (Ley, 1979).

Farm animal feed is often contaminated with human pathogens, such as salmonellae and other Enterobacteria. Irradiation decontamination treatment of mixed animal feeds for farm animals would be an effective approach to the reduction in numbers of these *micro-organisms*. A dose of approximately 8 kGy has been recommended (Ley, 1972). In pet foods, radiation doses of 5–7.5 kGy would be an effective treatment for the reduction in pathogenic *micro-organisms* (Ley, 1972). A radiation dose of 5 kGy has been recommended for the reduction of microbial contamination of *fish* protein concentrate powder, which is used as a flavouring agent in pet food (Tsuji, 1983).

See also Toxicology.

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Anisakis *see* Parasites.

Antioxidants *see* Additives.

Apple (*Malus* spp.)

Purpose of irradiation

For insect disinfestation (e.g. codling moth, fruit flies) and for shelf-life extension by delaying ripening, and controlling fungal decay and disease (e.g. scald), the recommended dose is less than 1 kGy.

Insect disinfestation

A radiation dose of 0.075 kGy prevented the development of adult fruit flies, when eggs or larvae were irradiated in 'Granny Smith' apples (Jessup *et al.*, 1992). Doses up to 0.1 kGy had no adverse effects on the external or internal appearance of apples. Disinfestation against the Queensland fruit fly, Mediterranean fruit fly and codling moth could be achieved with a dose of 0.6 kGy, with no effect on the sensory quality in 'Jonathan' or 'Granny Smith' apples (Rigney *et al.*, 1985).

Shelf-life extension

Irradiation, below 1 kGy, may delay the *ripening* and senescence of apples. Initial softening occurs but, following storage, irradiated apples are firmer than non-irradiated *fruit* (Thomas, 1986). In a study of 'Red Delicious' apples, radiation doses, up to 1 kGy, resulted in loss of firmness and lower acidity, but hydrolysis of *starch* was retarded (Olsen *et al.*, 1989). All apples surpassed the export standard for firmness after 11 months. Similar results have been reported for 'Granny Smith' apples treated with doses of approximately 0.5 kGy (Narvaiz *et al.*, 1988).

A number of factors influence the final quality of irradiated apples, including cultivar, time of irradiation, and storage conditions (Narviaz *et al.*, 1988). Keeping the radiation dose to a minimum will preserve the sensory quality of the *fruit*. *Combination treatments* have been used to minimize the radiation dose used to treat apples (Thomas, 1986). The effects of a combination of a low radiation dose plus modified atmospheres, surface coating, chemicals and heat appear to be inconclusive.

The possibility of increasing the storage life of apples, by controlling fungal pathogens, such as *Penicillium* spp., and browning disorders, such as scald, has been investigated. Doses above 1 kGy are required, but these result in adverse effects on the *fruit*, primarily softening, and internal breakdown, known as 'core flush' (Thomas, 1986).

Potential application

There is potential for irradiation insect disinfestation of apples, with a possible improvement in shelf-life. Irradiation of apples to a maximum dose of 0.4 kGy is permitted in China (see Table 10, page 86) and there has been successful test marketing of irradiated apples in Shanghai (see Table 11, page 98) (Moy, 1988). The *economic* benefits of irradiating apples in China have been demonstrated (Zu and Sha, 1993). Marketing of irradiated apples took place in the USA in 1988 (Terry and Tabor, 1988).

See also Fruit and vegetables; Insect disinfestation; Legislation; Market trials; Ripening and senescence.

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Apple juice *see* Juice.

Applications

The range of applications of *ionizing radiation* for food are shown in Table 1.

See also Commercial applications; Legislation; Market trials.

Apricot (*Prunus armeniaca*)

Irradiation could be used to control *insect* infestation in apricots. A radiation dose of 0.5 kGy, which would give good control the Mediterranean fruit fly, did not adversely affect the sensory quality of the *fruit* (Moy *et al.*, 1992). There could be *economic* benefits associated with the use of irradiation as a quarantine treatment for apricots, providing an alternative to methyl bromide fumigation (Forsythe and Evangelou, 1993). Legal clearance for the irradiation disinfestation of apricots is given in China (see Table 10, page 86).

The moulds, *Monilinia fructicola* and *Rhizopus stolonifer*, cause post-harvest brown rot in apricots. Doses in

Table 1 Main purposes of food irradiation and recommended dose ranges.

Purpose	**Food**	**Effect of radiation**	**Approx dose range (kGy)**
Extend storage life	Vegetables such as potatoes, onions, garlic	Inhibition of sprouting	0.05–0.15
	Fruit	Delay ripening	0.2–1
Prevent post-harvest losses	Cereals, flour, fresh and dried fruit, other products liable to insect infestation	Destruction of insects	0.15–1
Extend chill shelf-life	Meat, poultry, fish, ready meals	Reduction of micro-organisms that cause spoilage	0.5–3
	Fruits and certain vegetables	Reduction in populations of moulds and yeasts	1–3
Prevent food-borne illness	Meat, poultry, fish	Destruction of various parasites	0.03–6
	Meat, poultry, fish	Destruction of pathogenic bacteria e.g. *Salmonella, Listeria, Campylobacter*	3–7
Minimize contamination of food to which ingredients are added	Spices and other dried food ingredients	Reduction in numbers of micro-organisms	5–10
Shorten food drying and cooking times	Dehydrated vegetables and fruits, legumes	Depolymerization of pectin, cellulose and starch	3–10
Sterilization to produce shelf-stable products	Meat, poultry, ready meals	Destruction of micro-organisms, inc. spore-formers	up to 50

the range 1–3 kGy, which would control fungal decay, caused softening and discolouration of the *fruit* skin and flesh (Thomas, 1986). Adverse effects increased with dose. In addition, a number of other factors, including *fruit* variety, environmental conditions, and timing of irradiation, affected final *fruit* quality.

See also Insect disinfestation; Ripening and senescence.

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Apricot – dried *see* Dried fruit.

Artichoke – globe (*Cynara scolymus*)

In globe artichokes, radiation doses of 1 kGy and above, appropriate for controlling fungal rot by *Botrytis* spp., caused stem pitting and internal and external discolouration (Bramlage and Lipton, 1965).

Reference

Bramlage, W.J. and Lipton W.J. (1965) *Gamma Radiation of Vegetables to Extend Market Life*, Market Research Report No. 703, Agricultural Research Service, US Dept. of Agriculture, Washington, DC, pp. 10–11.

Artichoke – Jerusalem (*Helianthus tuberosus*)

Doses in the range 0.05–0.15 kGy inhibited sprouting in Jerusalem artichoke tubers. Radiation treatment extended storage life but there was a high incidence of rotting (Mikaelsen, 1959).

Reference

Mikaelsen, K. (1959) Irradiation of root crops, *International Journal of Applied Radiation and Isotopes*, **6**, 171–3.

Ascorbic acid (vitamin C)

General

The major dietary sources of vitamin C are *fruits* and *vegetables*. Animal sources (e.g. the liver) may contain small quantities.

Vitamin C is essential for the synthesis of structural proteins such as collagen. It combats the effects of active oxygen-derived species, such as the superoxide and *hydroxyl radicals* and singlet oxygen, in the body. Deficiency leads eventually to scurvy, which involves bleeding from the gums and into the joints, tissue fragility, and easy bruising; less extreme effects include fatigue and reduced resistance to infections.

Ascorbic acid has strong reducing properties and, in solution, is readily oxidized to dehydroascorbic acid, particularly at alkaline pH values. Dehydroascorbic acid is almost as active biologically as ascorbic acid. Isoascorbic acid has reducing activity and is used as a food *additive* (e.g. to limit loss of *nitrite* in the processing of cured *meats*), although it has only about 5% of the biological activity of ascorbic acid.

Radiation sensitivity

Ionizing radiation initially induces oxidation of ascorbic acid to dehydroascorbic acid (Barr and King, 1956). This reaction (in which the biological activity of the *vitamin* is retained) has been found to occur in many studies of irradiated *fruits* and *vegetables*. Further irradiation eventually leads to losses of activity as biologically non-functional products are formed.

Low doses of γ-radiation, used to delay sprouting of *potatoes*, reduced ascorbic but not dehydroascorbic acid levels. However, during subsequent storage, ascorbate levels rose, so that the differences between irradiated and non-irradiated *potatoes* disappeared (Schrieber and Highlands, 1958). Similarly, losses of *ascorbic acid* in *orange* and *lemon juices*, irradiated at 16 kGy, were accompanied by near stoichiometric increases in dehydroascorbic acid (Romani *et al.*, 1963).

Losses of about 16% ascorbic acid occurred in 3 kGy irradiated freeze dried *apples*. *Tomatoes* lost between about 8 and 20% according to the state of ripeness of the *fruit* (Maxie and Sommer, 1968). In other studies, virtually no losses of vitamin C (nor of the B-vitamins *riboflavin*, *niacin* or *thiamine*) were detected in *mangoes*, *papayas*, *lychees* or *strawberries*, irradiated at 2 kGy (Beyers *et al.*, 1979). No vitamin C losses were detected in *grapefruits* irradiated at up to about 1 kGy (Moshonas and Shaw, 1984).

Overall, the most likely changes occurring in low dose irradiated *fruit* and *vegetables* seem to be the conversion of a proportion of ascorbate to dehydroascorbate, and, sometimes, a small reduction in total vitamin C level. This reduction may then be reversed in intact *fruits* and *vegetables* as metabolism continues.

See also Vitamins; Fruit and vegetables.

References

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Asparagus (*Asparagus officinalis*)

A potential *application* of irradiation is for *insect disinfestation* of asparagus (CAST, 1989). In addition, very low radiation doses (0.05–0.15 kGy) result in the inhibition of elongation and curvature of asparagus spears. Doses above 0.15 kGy are considered to be detrimental to quality and storage life. However, studies in South Africa (van der Linde, 1982), using a combination of a dose of 1–1.5 kGy, with PVC wrapping and cold storage, at 6°C, resulted in a 2–3 fold increase in the shelf-life of white asparagus.

Although irradiation can beneficially retard senescence of asparagus, the *economic* feasibility of the technology is doubtful (Morris, 1987). Post-harvest growth of asparagus spears can be controlled more economically by alternative methods, such as strict temperature control and modified atmosphere storage.

See also Legislation.

References

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van der Linde, H.J. (1982) Progress in food irradiation: South Africa, *Food Irradiation Information*, **12**, 100–118.

Aspergillus *see* Moulds.

Atchar

Mango atchar is an oil-based pickle, popular in South Africa. The product consists of green *mangoes*, salt and *spices*. Storage in sealed plastic containers is limited by fermentation of the product caused by contaminating *yeasts*. Irradiation of mango atchar with a dose of 4 kGy controlled *yeast* growth and increased the shelf-life of the product (Redelinghuys, 1985).

Legal clearance for irradiation of mango atchar, up to maximum of 4 kGy, is given in South Africa (see Table 10, page 86).

See also Legislation.

Reference

Redelinghuys, H.J.P. (1985) The radurisation of atchar, *SAAFOST '85*, Proceedings of the Eighth Biennial Congress of the South African Association for Food Science and Technology, pp. 422–25.

Aubergine (*Solanum melongena*); Brinjal or Egg-plant

The use of irradiation to control fungal rot, by *Botrytis cinerea*, and improve the shelf-life of aubergines has been investigated (Stegeman, 1982). A combination of a hot water dip (45°C) and a radiation dose of 0.5 kGy–0.75 kGy delayed senescence and decreased weight loss during storage. However, this was accompanied by a decrease in resistance of aubergines to *B. cinerea* and an unacceptable browning of the calyx.

A preliminary study of green brinjals suggested that a radiation dose of 1 kGy could be used to improve shelf-life (Avadhani and Lian, 1985).

References

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Avocado (*Persea americana*)

To increase shelf-life by delaying ripening and senescence, the recommended dose is 0.025–0.1 kGy.

Product characteristics

Avocados are very sensitive to radiation. The threshold dose for damage, and optimal dose for delayed *ripening* and senescence, depends on a number of factors including the variety, geographical origin, and degree of maturity of the *fruit* (Thomas, 1986). Even doses below 0.1 kGy can cause damage, mainly in the form of vascular strand browning and internal discolouration. Rapid acceleration of this discolouration occurs on exposure of the flesh of the irradiated *fruit* to air.

A combination of heat and irradiation increased the shelf-life of the 'Fuerte' variety of avocados. A hot water dip (10 minutes at 46°C), individual wrapping in PVC foil, followed by irradiation at 0.025 kGy, and storage at chill temperatures resulted in delayed senescence (Karmelic *et al.*, 1985; Ang *et al.*, 1986). In a commercial trial of this *combination treatment*, in Chile, avocados were shipped to the Netherlands and subsequently stored, simulating conditions of retail distribution (Ang *et al.*, 1986). Better consumer quality in terms of appearance, *texture* and *flavour* were demonstrated for the treated fruit.

A dose of 0.075 kGy prevented the development of adult Queensland fruit fly, when eggs and larvae were irradiated in avocados (Jessup *et al.*, 1992). Browning of the vascular tissue of avocados ('Fuerte' variety) was observed after treatment.

Potential application

The use of irradiation for *insect disinfestation* and shelf-life extension of avocados, as an alternative to chemical fumigation and cold treatment, may be impractical owing to the radiation sensitivity of the *fruit*.

See also Ripening and senescence; Legislation.

References

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Karmelic, J., Rubio, T. and Urbina, C. (1985) Preservation of fresh avocados by irradiation, in *Radiation Disinfestation of Food and Agricultural Products*, Proceedings of an International Conference, Honolulu, 1983, (ed. J.H. Moy), pp. 148–59.

Thomas, P. (1986) Radiation preservation of foods of plant origin. Part IV. Subtropical fruits: citrus, grapes and avocados, *CRC Critical Reviews in Food Science and Nutrition*, **24**(1), 53–88.

B

Bacon *see* Meat; Nitrite reduction.

Bacteria *see* Aeromonas; Campylobacter; Clostridium botulinum; D-value; Escherichia coli; Lactobacillus; Listeria; Micro-organisms – relative resistances; Micro-organisms – safety; Pseudomonas; Salmonella; Shigella; Spores – sensitization to heat; Staphylococcus aureus; Toxins; Vilerioj Yersinia.

Banana (*Musa* spp.)

For shelf-life extension by delaying ripening, the recommended dose is 0.2–0.5 kGy.

Treatment

Treatment with low doses of *ionizing radiation* causes a delay in *ripening* of bananas and can increase the shelf-life of the *fruit* 2–3 fold (Thomas, 1986). The maximum delay in *ripening* occurs with pre-climacteric bananas; as *fruit* maturity progresses, the treatment is less effective. Doses in excess of approximately 0.7 kGy result in blackening, skin splitting, and softening and mealiness of the *fruit* pulp. The variety of banana influences both the optimum dose for maximum shelf-life and the threshold dose for damage. The temperature of post-irradiation storage influences the rate of *ripening*.

A combination of heat treatment (50°C, 5 minutes) and 0.25–0.35 kGy increased the storage life of bananas by 3–5 days. Hot water treatment was used as a supplementary process to control stem-end rot (Padwal-Desai *et al.*, 1973).

Guidelines

A Code of Good Irradiation Practice for Insect Disinfestation of Fresh Bananas, Mangoes and Papayas, ICGFI Document No. 1, 1991, is published by the International Atomic Energy Agency.

Product characteristics

Treatment of bananas at the optimal dose for *ripening* delay does not adversely affect sensory properties. This is the case if *fruits* are subsequently ripened with or without ethylene. Fully yellow, irradiated bananas may be firmer than untreated *fruits* (Thomas, 1986).

When bananas were treated shortly after harvesting at the mature green stage (0.4–0.5 kGy), and then stored normally, losses of mature yellow bananas were reduced from 18% to 2% (Huyzers and Basson, 1985).

Potential application

The use of irradiation to delay *ripening* of bananas appears to be technically feasible but may not be economically viable (Morris, 1987). Cheaper alternative treatments are available, including temperature management, ethylene removal and controlled atmosphere storage.

Legal clearance for the treatment of bananas is given in South Africa (see Table 10, page 86). Successful marketing trials of irradiated bananas have been reported (Huyzers and Basson, 1985).

See also Ripening and senescence.

References

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Barley (*Hordeum* spp.)

Malting is a process in which barley is germinated and the very young seedlings are dried to produce malt for brewing beer. Controlling the germination of barley during malting, by irradiation, has been investigated.

Doses of 0.01–0.1 kGy have a stimulating effect on germination of barley. It has been suggested that irradiation could be used to shorten the malting process and increase the production capacity of malting plants (Farkas, 1990). In addition, the treatment of dried barley, with doses of 0.25–0.5 kGy, retards root growth but does not prevent the emergence of shoot tips and tendrils during malting. Malt of normal enzymatic constitution and capacity is produced, while malting losses caused by root growth are reduced.

Although irradiation of barley with doses of 0.75 kGy can produce normal malts (Atvar *et al.*, 1985), higher doses increase malt yields but decrease alpha-amylase activity. Addition of gibberellic acid partially alleviates the detrimental effect.

Irradiation with doses up to 1 kGy is recommended for the *insect disinfestation* of cereals. Bacterial contamination could be controlled, to a certain extent, at this level.

See also Cereal grains; Micro-organisms – relative resistances.

References

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Farkas, J. (1990) Status of food irradiation in Eastern Europe, *Radiation Physics and Chemistry*, **35**(1–3), 236–41.

Bean *see* Legume.

Becquerel

The becquerel (Bq) is the SI unit of *radioactivity*. It is equal to one nuclear transformation per second. It replaces the older unit, the *curie* (Ci).

A typical irradiation facility may use:

500 000 Ci = 500 kCi = 18.5 PBq (petabecquerels = 10^{15} Bq).

Beef *see* Meat.

Beetroot (*Beta vulgaris*)

Inhibition of sprouting of beetroot occurred at doses between 0.05–0.15 kGy (Mikaelsen, 1959). However, the treatment may increase the rate of rotting of this root vegetable.

Reference

Mikaelsen, K. (1959) Irradiation of root crops, *International Journal of Applied Radiation and Isotopes*, **6**, 171–3.

Benzo (α) pyrene quinone

Irradiation of lipid-rich foods may result in the production of low levels of products such as benzo (α) pyrene quinone (Gower and Wills, 1986) that, whilst not unique, are known to be carcinogenic. The quinone has been shown to arise from the oxidation of benzo (α) pyrene, mediated by the *lipid* peroxidation caused by radiation.

See also Toxicology.

Reference

Gower, J.D. and Willis, E.D. (1986) The oxidation of benzo (α) pyrene mediated by lipid peroxidation in irradiated synthetic diets, *International Journal of Radiation Biology*, **49**, 471–84.

Berries

The possibility of using irradiation to reduce fungal spoilage (*Botrytis* spp.) on berries, and so prolong shelf-life, is commercially attractive. Limited studies on the effects of irradiation on blackberries (*Rubus* spp.), blackcurrants (*Ribes nigrum*), blueberries (*Vaccinium myrtillus*), cranberries (*V. macrocarpon*) and raspberries (*Rubus* spp.) suggest that doses of 1.5 kGy or below are appropriate (Eaton *et al.*, 1970; Thomas, 1986; Vidal, 1963).

The primary factor limiting the quality of irradiated berries is tissue softening. For most berries, it is difficult to choose a dose that increases shelf-life significantly, without adversely affecting sensory properties. A number of factors affect final *fruit* quality, including cultivar, treatment conditions, such as *packaging*, packaging atmosphere, storage temperature, and time between irradiation and harvest.

See also Strawberry.

References

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Biotin (vitamin B10)

General

Major dietary sources of biotin include liver, yeast, the bran and germ of *rice* and other grains, and *egg* yolk. Secondary sources include red *meats* and *fish*, *pulses*, *milk*, *fruits* and *vegetables*. Biotin is relatively stable, e.g. to heating, at near neutral and mildly acidic pH values in foods.

Radiation sensitivity

Biotin is very radiation resistant in foods. Sterilizing doses of *gamma* and *electron beam* irradiation did not significantly reduce levels in *poultry* (Black *et al.*, 1983), or in *eggs*, at doses up to 50 kGy (Kennedy, 1965). Its relative stability to irradiation is reduced in the presence of *oxygen* more so than that of the other *vitamins* (Watanabe *et al.*, 1976).

See also Vitamins.

References

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Watanabe, H., Aoki, S. and Sato, T. (1976) Gamma ray inactivation of biotin in dilute aqueous solution, *Agricultural and Biological Chemistry*, **40**, 915.

Blackberry *see* Berries.

Blackcurrant *see* Berries.

Blueberry *see* Berries.

Botrytis *see* Moulds.

Botulism *see* Clostridium botulinum.

Bovine spongiform encephalopathy *see* BSE.

Bread *see* Cereal grains; Cereal products.

Brinjal *see* Aubergine.

Broccoli (*Brassica oleracea*)

The use of doses of 1 kGy, and above, to control surface *micro-organisms* on broccoli has been shown to accelerate maturation, i.e. more rapid yellowing and flower bud opening (Lopez-Dominguez *et al.*, 1988). In contrast, irradiation has been shown to inhibit bud opening, thus preserving the quality of the product (Salunkhe, 1961).

References

Lopez-Dominguez, A.M., Willemot, C., Castaigne, F., Cheour, F. and Arul, J. (1988) Effets de l'irradiation aux rayons gamma sur la conservation du brocoli (*Brassica oleracea* var. Italica), *Canadian Journal of Plant Science*, **68**, 871–6.

Salunkhe, D.K. (1961) Gamma radiation effects on fruits and vegetables, *Economic Botany*, **15**(1), 28–56.

BSE

BSE (bovine spongiform encephalopathy) is a degenerative disease of the brain tissue of cows. The causative agent is identical or near-identical to the agent of scrapie in sheep. It is related to other transmissible encephalopathies, which include kuru and Creutzfeldt-Jacob disease ('CJD') and its variants, fatal familial insomnia in man, as well as similar diseases affecting other species (e.g. mink and deer).

Although the agent has some of the characteristics of a slow *virus*, it has not been isolated or cultured. Whilst the genetics of scrapie make it difficult to accept that the agent does not contain nucleic acids, there is evidence that it is an infectious protein, called a prion.

There was major concern in the late 1980s at the large rise in the incidence of BSE, which was thought to result from the feeding of ruminant-derived-protein to ruminants in the UK (DoH, 1989). Such feeding was subsequently banned. Unlike *viruses*, prions have a high resistance to heat and to chemicals such as formaldehyde and glutaraldehyde and higher resistance to ultraviolet and *ionizing radiation* (Collee, 1993).

References

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DoH (1989) Report of the Working Party on Bovine Spongiform Encephalopathy, London, Department of Health.

Bulbs *see* Garlic; Onion.

C

Cabbage

If cabbage and cauliflower are irradiated above a dose of 3 kGy to control decay, there is a reduction in quality (Salunkhe, 1961). A potential use of irradiation for the *insect disinfestation* of cabbage and cauliflower, at doses of 1 kGy or below, has been suggested (CAST, 1989).

References

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Caesium-137 *see* Radionuclide.

Calciferol (vitamin D)

General

The major dietary sources of vitamin D are oily sea *fish*, especially *fish* liver oils, and to a lesser extent *egg* yolk, butter and *beef*, as well as deliberately fortified margarines, low-fat spreads and *milk* products. *Fruits* and *vegetables* are not important sources of D vitamins.

Chemically, the D vitamins are a group of steroid derivatives, the most important of which are calciferol (vitamin D2) and cholecalciferol (vitamin D3). *In vivo* they are required for absorption and transport of dietary calcium and phosphate. The most obvious result of deficiency is calcium malabsorption, with consequent impairment of bone development and, in the young, the onset of rickets.

Radiation sensitivity

Although the presence of water increases sensitivity, the D vitamins are relatively stable to *ionizing radiation* in their normal lipid-rich food environments. At doses up to 15 kGy, cholecalciferol is more radiation resistant than vitamin A or vitamin E. Irradiation resistance of vitamin D in *fish* oils was even greater than in solvents, such as iso-octane, presumably due to the presence of tocopherols and other naturally-occurring antioxidants (Knapp and Tappel, 1961).

See also Vitamins.

Reference

Knapp, F.W., and Tappel, A.L. (1961) Comparison of the radiosensitivities of the fat-soluble vitamins by gamma irradiation, *Agricultural and Food Chemistry*, **9**, 430–3.

Campylobacter

General

Campylobacter has become recognized as the major cause of acute gastroenteritis in developed countries in recent years, with numbers of cases substantially exceeding those caused by salmonellae. The infective dose is thought to be only a few hundred cells. The disease is widespread, but usually mild and self-limiting. Consequently, campylobacteriosis has not received the public prominence that has been accorded to the sometimes more life-threatening cases of salmonellosis and listeriosis.

The organism is a thin spirally-curved Gram-negative rod. Most infections are caused by *C. jejuni*, but the closely related species, *C. coli* and *C. laridis*, cause less frequent illness too. The organism is a strict microaerophile, i.e. it requires low levels of oxygen for growth to occur. Furthermore, the temperature range for growth of *Campylobacter* is narrow and high, between about 30 and 47°C. Consequently, although campylobacters may survive in foods, they are generally not able to multiply.

A wide variety of wild and domestic animals, including cattle, sheep, poultry and pet animals, harbour campylobacters, so that they are common contaminants of uncooked foods. Unpasteurized *milk* has caused some of the largest recognized outbreaks.

Radiation resistance

Along with their sensitivity to heat and to oxygen, *Campylobacter* species have low radiation tolerance, well below that of salmonellae and listerias. The *D-value* of *C. jejuni*, irradiated in raw *beef* at 18°C, was about 0.14 kGy (Tarkowski *et al.*, 1984), and in chilled *turkey*, about 0.18 kGy (Lambert and Maxcy, 1984). The *D-values* of four species (*C. jejuni*, 3 strains; *C. coli*, 1 strain; *C. fetus*, 1 strain; *C. lari*, 1 strain) irradiated in *poultry* meat ranged from 0.12 to 0.25 kGy (Patterson, 1995). Differences within species were sometimes greater than differences between species, e.g. the *D-value* of one strain of *C. lari* was 0.12 kGy and of another 0.25 kGy.

References

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Cantaloupe *see* Melon.

Capsicum; Green pepper, Bell pepper, Sweet pepper

At doses in excess of 1 kGy, appropriate for inhibiting *mould* growth, the sensory quality of peppers was adversely affected (Bramlage and Lipton, 1965). The symptoms of damage were softening, yellowing and discolouration.

The after-ripening of red pepper (*Capsicum annuum*) was substantially accelerated by 0.02 kGy; above 0.1 kGy, formation of carotenoid pigments was inhibited (Farkas et al., 1966). Radiation doses below 0.5 kGy accelerated *ripening* in green chillies (*Capsicum frutescens*) (Avadhani and Lian, 1985).

A dose of 5 kGy is recommended for treating dried hot peppers to control microbial spoilage and prevent *insect* infestation (Chen, 1992). Irradiated packaged dried peppers retained their sensory quality after 9 months storage under ambient conditions.

References

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Chen, Q. (1992) Irradiation of hot peppers to improve their hygienic quality, in *Asian Regional Cooperative Project on Food Irradiation Technology Transfer*, International Atomic Energy Agency, Vienna, pp. 37–49.

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Carambola (*Averrhoa carambola*); Starfruit

The use of irradiation for *insect disinfestation* of the carambola has been considered (CAST, 1989). A dose of 0.05 kGy applied to infested carambolas prevented emergence of Caribbean fruit flies (von Windeguth, 1992). Doses of 0.2 kGy, and above, caused radiation injury of the *fruit*, in the form of darkening of the ribs and outer edges of the wings (Vijaysegaran, 1991). *Fruit ripening* may be accelerated. At 1 kGy, softening and adverse changes in appearance were observed.

References

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Carbohydrates

Apart from water, the major constituents of most foods are carbohydrates, *proteins* and *lipids*. Irradiation of low molecular weight food carbohydrates, such as glucose, mannose, ribose and lactose, results in the formation of low levels of *radiolytic products* mostly derived from reaction of *hydroxyl radicals* (OH°), generated from water, with the sugar. A predominant reaction is the oxidation of hydroxyl groups, often with loss of a neighbouring hydroxyl group. Products such as 2-deoxygluconolactone and gluconic acid are formed, and the pH value of simple sugar solutions falls (von Sonntag, 1980). Carbohydrates irradiated in the solid state are generally more resistant than those irradiated in solution.

Irradiation of high molecular weight carbohydrates (*starch*, *pectin*, *cellulose*, *carrageenans*, etc.)

sometimes causes major changes in the physical properties of the foods that contain them. Properties such as viscosity, mechanical strength, swelling and solubility are likely to change in such a way as to reduce their functionality in a food, but sometimes change to improve their effectiveness for a particular function.

Irradiation of lignocelluloses, in woody materials, has been shown to increase their subsequent biodegradability by *micro-organisms* such as *Flavobacterium* species (Bhatt *et al.*, 1992). The limited breakdown that occurs increases their susceptibility to the micro-organism's hydrolytic exoenzymes. The properties of *gums*, such as Karaya gum (Le Cerf *et al.*, 1991) change greatly on irradiation with, for example, very large increases in solubility, falls in viscosity and loss of water-swelling properties.

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Carbon monoxide

Furuta *et al.* (1992) showed that the *detection* of radiolytically derived carbon monoxide (CO) could be used to detect irradiated *meat* products. After heating samples in a microwave oven, headspace gas was analysed by gas chromatography using a flame ionization detector. After storage for one year, CO levels in irradiated samples were still higher than in unirradiated controls. The method has the advantage over techniques such as *ESR* in that it can be used for boneless food samples.

See also Detection.

Reference

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Caribbean fruit fly *see* Insects.

Carob gum *see* Gums.

Carotene *see* Retinol (vitamin A).

Carrageenan

Iota- and kappa- carrageenans are widely employed as food thickening and gelling agents. Irradiation causes depolymerization of carrageenans, although this is less marked when dry powders are irradiated as compared with gels. The viscosity and gel strengths are substantially reduced by irradiation, e.g. by 50% or so, using 10 kGy, depending on the preparation (Marrs, 1988).

See also Carbohydrates; Gums.

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Carrot (*Daucus carota*)

Sprout inhibition of carrots can be achieved using doses of approximately 0.1 kGy (Mikaelsen, 1959). Storage rots may be exacerbated at higher doses.

The use of irradiation to control microbial spoilage of prepared sliced carrots may be limited by softening of the tissue, at doses in excess of 1 kGy (Beczner-Hegyesi *et al.*, 1972). Optimal hygienic and organoleptic properties of grated carrot were achieved with a treatment of 0.5 kGy and storage at 4°C (Biosseau *et al.*, 1991).

See also Inhibition of sprouting.

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Cashew nut *see* Nut.

Cauliflower *see* Cabbage.

Cellulose *see* Pectin and cellulose.

Cereal grains

For insect disinfestation of grain (e.g. wheat, maize, rice, barley), the recommended dose is 0.2–0.5 kGy. To increase storage life by reduction of microbial contamination, the recommended dose is 2 kGy and above.

Insect disinfestation

Insects are a major problem for storage of grains and seeds. *Insect disinfestation* is currently undertaken using gas fumigants, such as methyl bromide, but these are considered to pose a health risk and are being phased out in many countries.

The radiosensitivity of a number of species of *insect* pests of stored products has been determined (Tilton and Brower, 1987). Many factors affect the sensitivity of a species, including *insect* stage and environment. In general, the Coleoptera, grain weevils (e.g. *Sitophilus granarius, S. oryzae, S. zeamais*) and grain beetles (e.g. *Tribolium confusum, Rhizopertha dominica*) are most sensitive. Arachnids, including the grain mites (e.g. *Acarus siro*), have intermediate sensitivity. Lepidoptera, such as the Angoumois grain moth (*Sitotroga cerealella*) and the Indian meal moth (*Plodia interpunctella*), are the most resistant of stored product pests.

An effective radiation dose must be determined for a specific *insect* species, food product and set of conditions. If grains are infested with many species, a dose of 0.5 kGy will control even the most resistant beetle species and the most immature stages of mites and moths (Tilton and Brower, 1987). Doses in this range have minimal effects on the organoleptic and functional properties of cereals (Giddings and Welt, 1982).

The use of *combination treatments* can reduce the radiation dose required for disinfestation, which confers advantages for product quality. The combination of irradiation plus microwave or infra-red radiation, high temperature, hypoxia, and chemicals may achieve this goal (Tilton and Brower, 1987).

Guidelines

A Code of Good Irradiation Practice for Insect Disinfestation of Cereal Grains (ICGFI Document No. 3) is published by the International Atomic Energy Agency (1993).

Controlling the growth of micro-organisms

Cereal grains are generally preserved by drying. Their low moisture content prevents spoilage due to microbial action. However, during storage, moisture levels may rise in grains that are not handled according to good manufacturing practice. Favourable conditions for microbial growth are created and moulds, such as *Aspergillus* and *Penicillium*, can be a problem (Badshah *et al.*, 1992). Radiation doses of the order of 2 kGy and above are required to eliminate bacterial and fungal deterioration of grains. At these higher doses, chemical changes in grains induced may be undesirable (Lorenz, 1975).

Maize grains treated with a dose of 0.8 kGy lost their seed viability (Amoaka-Atta, 1981). The reduction in seed viability helps maintain low moisture content and reduces *mould* growth.

Fears have been expressed that irradiation will enhance aflatoxin production in grain. There was an increase in aflatoxin production in inoculated wheat, but a decrease in production in *barley* and maize, when grains were irradiated prior to inoculation (Paster and Bullerman, 1988). Factors that affect aflatoxin production include the number of spores in the inoculum, grain condition, relative humidity, and other environmental factors.

Packaging

Packaging for products, such as cereal grains, subjected to long-term storage after irradiation should be resistant to *insect* reinfestation. Factors that need to be considered in the selection or development of *insect* resistant packages for radiation-disinfested foods are reviewed by Highland (1991).

Product characteristics

The effects of irradiation on cereal grains have been investigated by monitoring changes in flour, cereal components, such as gluten and *starch*, and the baking quality of *cereal products*, such as bread and cakes (Giddings and Welt, 1982; Lorenz, 1975). In general, low radiation doses appropriate for *insect* disinfestation cause minimal effects, but higher doses needed for microbial decontamination lead to undesirable changes.

Nutritional value

Cereal grains are important source of *vitamins, minerals, protein* and complex *carbohydrates*. Thus nutritional losses incurred by irradiation treatment are a major concern.

The nutritional effects of irradiation on foodstuffs have been reviewed by Diehl (1990). Losses of *vitamins* occur in irradiated cereals, particularly *thiamine* and *tocopherol*, at doses in excess of 1 kGy. A number of factors affect the extent of *vitamin* losses including dose, dose rate, type of cereal grain, *packaging, temperature* and time of storage (Hanis *et al.*, 1988; Khattak and Klopfenstein, 1989a; Kovacs, 1991). Losses can be minimized by the use of oxygen-free packaging and irradiation at low temperatures (Diehl, 1991). Sulphur-containing amino acids in cereals are reported to be radiation sensitive (Khattak and Klopfenstein, 1989b).

Improvement in the levels of certain nutrients following irradiation of cereal grains has been reported (Diehl, 1991; Khattak and Klopfenstein, 1989b).

Detection

Irradiated grain could be detected using tests that detect *DNA* damage.

Potential application

Although there is legal clearance in many countries (see Table 10, page 86) for *insect disinfestation* of cereal grains and their products by irradiation, there is no commercial use, except in the Ukraine (see Table 5, page 32). Market trials of irradiated wheat germ and wheat bran have been undertaken in Hungary (Kovacs, 1991). The costs and benefits of radiation disinfestation of grain, using an *electron accelerator*, have been evaluated (Borsa and Iverson, 1993).

See also Barley; Cereal products; Economics; Facilities; Insect disinfestation; Moulds; Micro-organisms – relative resistances; Nutrition; Polyploidy; Rice.

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Cereal products

Treatment of *cereal grains* for *insect disinfestation* requires radiation doses up to approximately 0.5 kGy. Higher doses, of the order of 2 kGy or above, are required to reduce microbial contamination of grain. The effects of irradiation on the nutritional, sensory and functional characteristics of grain components, and on the cereal products prepared from irradiated grain, have been examined.

Proteins

The total *protein* content of wheat and wheat flour is unaffected at doses appropriate for *insect disinfestation* (Lorenz, 1975). The essential amino acid composition is unaffected but levels of free amino acids may increase at higher radiation doses, e.g. levels of free tyrosine in irradiated flour increased by approximately 13% at 2 kGy (Sreenivasan, 1974). In addition, *in-vitro* digestibility of wheat *proteins* is increased by irradiation.

Since gluten *proteins* are important factors that determine the functional properties of wheat, there is particular interest in the effect of irradiation on these *proteins*. Gluten in irradiated dry grains becomes weak, inelastic and too extensible; in moist grain, gluten undergoes the opposite changes, becoming stiff, with consequent loss of extensibility and cohesion (Lorenz, 1975). Significant breakdown of gluten, in terms of fragmentation and aggregation, may not take place much below 10 kGy (Paredes-Lopez and Covarrubias-Alvarez, 1984). No apparent differences were reported in wet gluten and *protein* solubility, in wheat grain irradiated up to 3 kGy (MacArthur and D'Appolonia, 1983).

Carbohydrates

At doses between 0.2–2 kGy, a reduction in *starch* content, and an increase in levels of water-soluble reducing sugars, e.g. glucose and maltose, occurs in irradiated wheat (Sreenivasan, 1974). The extent of depolymerization of *starch* depends on the water content of the grain.

Damage to *starch* is evident in the range 0.5–3 kGy and increases with increasing dose (MacArthur and D'Appolonia, 1984). This is reflected in a decrease in peak viscosity of *starch* pastes, a decrease in intrinsic viscosity values and an increased water-binding capacity. In addition, there is a decrease in swelling power and reduction in solubility values of irradiated *starch* samples.

It has been suggested that *starch* breakdown may be responsible for the reduction in power consumption when irradiated wheat is milled. A reduction in flour particle hardness appears to facilitate the grinding operation (Lorenz, 1975).

Pentosans, which are polysaccharides involved in the gas retaining properties of dough, may be affected by irradiation (Lorenz, 1975). A reduction in loaf quality of bread loaves made from irradiated wheat may be caused by pentosan damage.

Lipids

Although at practical radiation doses there is little change in the *lipids* in wheat (Lorenz, 1975), damage has been linked to the formation of a 'tallowy' odour in irradiated baked products. Peroxide values of wheat flour increase with dose and storage. The increase in peroxide levels during storage of wheat may be less in irradiated than in untreated samples.

Vitamins and minerals

Radiation doses up to approximately 0.5 kGy, which are recommended for the disinfestation of cereals, do not cause significant destruction of B-complex *vitamins* (Diehl, 1990). However, losses of *thiamine* are reported in wheat flour and rolled oats, even at 0.3 kGy, with levels exacerbated by storage and heating. Conversely, there may be an increase in *niacin* levels in bread made from irradiated flour. At radiation doses greater than 1 kGy, losses of B-vitamins increase, and are intensified by storage and heating. In addition, levels of *tocopherol* are sensitive to *ionizing radiation.*

Enzymes

Enzyme content is one of the attributes that determines the quality of cereals. At doses appropriate for treating cereals, *enzymes* are radiation resistant (Lorenz, 1975). Although amylase activity is unaffected *per se* (MacArthur and D'Appolonia, 1983), there is an increase in diastatic activity in irradiated wheat. An increase in maltose values is caused by radiation-induced degradation of *starch* that makes it more susceptible to enzymatic hydrolysis (Sreenivasan, 1974).

Baking properties of wheat flour

In general, doses suitable for grain disinfestation do not adversely affect the baking quality of the cereal products. Many factors influence the baking quality of wheat flour, including the variety of wheat, its *protein* and *starch* content ('hard' or 'soft' flour), storage conditions pre- and post-irradiation, formulation and processing technique.

At low radiation doses (1 kGy and below) an improvement in the baking performance of 'soft' wheat flours is reported (Paredes-Lopez and Covarrubias-Alvarez, 1984). The effect is minimal in hard wheat varieties. An increase in loaf size of bread baked from formulas containing only small amounts of added sugars has been found (Lorenz, 1975). It would appear that ionizing energy promotes *starch* breakdown leading to an increase in fermentable sugars, thus stimulating yeast activity and gas production. This effect is only evident in the absence of dough *additives.*

At medium radiation doses (1–10 kGy) overall bread quality of both 'hard' and 'soft' wheats is reduced as a function of dose (MacArthur and d'Appolonia, 1983; Paredes-Lopez and Covarrubias-Alvarez, 1984). Damage to *starch*, gluten and pentosans impairs gas retention and affects water-holding capacity; this exceeds any improvement due to higher gas production.

Sensory quality of baked goods

The shelf-life of bread could be substantially increased by controlling the 'rope' defect caused by the presence of the bacterium *Bacillus subtilis* (Farkas and Andrassy, 1981). At a storage temperature of 30°C, shelf-life increased by 50% in bread made from irradiated wheat flour. The organoleptic quality was unaffected at 0.75 kGy but *off-flavours* developed at 1.5 kGy. In general, off-odours are more pronounced than *off-flavours* in breads after cooking (Lorenz, 1975). A musty odour may be evident even at doses of the order of 0.5 kGy. Storage of flour may reduce adverse sensory changes in bread. Problems of increased crumb firmness, and staling rate, of bread made from irradiated wheat grain have been reported (Warchalewski and Klockiewicz-Kamińska, 1989).

The effect of irradiation on baked goods is reviewed by Lorenz (1975). In general, plain cakes and biscuits made from irradiated 'soft' wheat flour, treated with doses suitable for *insect disinfestation*, are unaffected. At doses of the order of 0.5 kGy, minor changes in *flavour* and odour have been observed. At approximately 1 kGy, crust, crumb *colour, flavour* and *texture* are impaired.

Microbial decontamination

Treatment of cereal products with doses appropriate for the control of *micro-organisms* results in adverse sensory changes. A *combination treatment* of a low radiation dose and mild heat could be an effective method for microbial decontamination of cereal products. Prepackaged chapattis (Indian unleavened bread) and sliced packaged bread remained *mould* free and shelf stable, for ten weeks at 30°C, after a treatment of 0.5 kGy followed by dry heat at 65°C for 30 minutes (Padwal-Desai *et al.*, 1973). Chapattis were acceptable after two months; the bread slices were stale.

Wheat flour is a basic ingredient in a wide variety of sauces, gravies, sausages, *meat* loaves, canned foods and confectionery. The use of irradiation to reduce microbial levels of wheat flour, for use as a food ingredient, may be feasible (Farkas, 1988). When irradiated wheat flour was added to canned *meat*, no effect on sensory quality was observed.

When semolina, purified from durum wheat, was irradiated at a dose of 5 kGy, pasta *colour* was improved but firmness of the cooked pasta was adversely affected; tolerance of pasta to overcooking decreased (Taha, 1990).

Potential application

Legal clearance for the irradiation of *cereal grains* and their products, for the purpose of *insect disinfestation*, is given several countries (see Table 10, page 86). There is permission, in France, for the microbial decontamination of *cereal grains*, flakes, muesli and germs.

See also Cereal grains; Lipids; Nutrition; Proteins; Starch; Vitamins.

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Cheese *see* Dairy products.

Chemiluminescence

When water is added to irradiated solids, a burst of light emission ('chemiluminescence') may occur. This can be detected by a suitably sensitive photomultiplier and correlated with radiation dose. Sensitivity can be increased by the addition of a secondary photosensitizer such as luminol. The technique works well with *dried vegetables* and *spices*, and has also been shown to be effective with some frozen foods – *chicken*, *fish* and *shrimp* (Bogl and Heide, 1985; Heide and Bogl, 1988; Sattar *et al.*, 1987).

A problem is that the level of enhancement of luminescence, by any particular radiation dose, varies greatly for different foods. For instance, 10 kGy irradiation of *spices* raised luminescence of some by up to 1000 fold and others not at all (Heide and Bogl, 1988). The technique is generally not thought to be as useful and informative as *thermoluminescence*.

See also Detection; Thermoluminescence.

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Cherry (*Prunus avium*)

For insect disinfestation (e.g. fruit fly, codling moth) and for extension of shelf-life by reducing fungal decay and delaying senescence, the recommended dose is less than 1 kGy.

Insect disinfestation

There is potential for irradiation to be used for the disinfestation of cherries against fruit flies or codling moth. Using doses up to 1 kGy, no significant effects on total soluble solids, firmness, external damage or *fruit* weight were recorded in cherries ('Rons seedling' variety) (Jessup *et al.*, 1992). Peduncle discolouration was observed at a dose of 0.6 kGy, but the *fruits* were classed as commercially acceptable. Cherry varieties vary in their radiation sensitivity. Softening, wrinkling and *flavour* changes at doses 0.6–0.8 kGy were demonstrated in Bing cherries (O'Mahony *et al.*, 1985).

Control of fungal spoilage

Fungal decay of sweet cherries is caused by *Monilinia* spp. and *Cladosporium herbarum* (brown rot). Doses in excess of 1 kGy could control these *micro-organisms* and extend the shelf-life of the *fruit*. However, at these dose levels, softening of the *fruit* is a major problem (Thomas, 1986). The threshold dose for *texture* changes appears to depend on a number of factors, including harvest maturity, variety and pre- and post-irradiation storage temperature.

See also Insect disinfestation; Fruit and vegetables.

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Chestnut *see* Nuts.

Chicken *see* Poultry.

Chlorophyll *see* Colour; Potato.

Cholecalciferol *see* Calciferol.

Cholera *see* Vibrio.

Citrus fruit

For insect disinfestation and control of microbial spoilage, the recommended dose is less than 1 kGy.

Insect disinfestation

Oranges, *lemons*, *grapefruit*, tangerines, limes, tangelos and kumquats are included in the citrus family. The kumquat (*Fortunella* spp.) is not a true citrus fruit.

Irradiation is a potential quarantine procedure against fruit flies for citrus fruits. The gas fumigant, ethyl dibromide, is banned in several countries and methyl bromide is being phased out for *insect disinfestation* in the USA. Very low radiation doses prevent all species of fruit fly from developing to the adult stage or result in sterile insects (Burditt, 1982). A minimum dose of 0.15 kGy is recommended. In a commercial process, most of the product would receive a dose that may be two or three times the minimum. Thus in practice, citrus fruit need to tolerate doses in the range 0.3–0.45 kGy.

Control of microbial spoilage

Spoilage of citrus fruit caused by fungal pathogens is a problem in the postharvest handling, storage, transport and marketing of citrus fruit. Decay can be caused by a number of *moulds* including *Alternaria* spp., which causes stem end rots, and blue and green moulds caused by *Penicillium* spp. Irradiation have been considered as an alternative to chemical fungicides applied to the surface of the fruit, thus avoiding the problem of chemical residues.

Extensive studies on the use of irradiation to control storage disease in citrus fruit have been reviewed by Thomas (1986). Radiation doses in the range 0.5–2 kGy have been shown to control fungal spoilage, depending on type and size of fungal population, and initial microbial load of the fruit.

Canker is a citrus plant disease caused by the bacterium *Xanthomonas campestris*. Control of this disease by wax treating, *packaging*, heat treatment (5 minutes at 50°C) and a dose of 0.7 kGy has been recommended (Montalban *et al.*, 1993).

Product characteristics

The use of irradiation is mainly limited by the damage caused to the fruit peel, in the form of pitting and discolouration (Thomas, 1986). Radiation injury occurs at doses in excess of 1 kGy, although it may be observed at doses as low as 0.25 kGy. The threshold dose for peel damage depends on citrus species, variety, maturity at harvest, time delay between harvest and irradiation and post-irradiation temperature and time. Severity of damage increases with dose, storage time and storage temperature. Tangerines may be more sensitive than *oranges* in this respect.

Radiation-induced damage to peel tissues during storage can be reduced by storage at low temperatures (Moy and Nagai, 1985) or a pre-irradiation hot water dip of 52°C for 5 minutes (Barkai-Golan, 1992). The hot water dip also reduces the incidence of *mould* infection on storage. Combinations of low-dose irradiation with heat, chemicals and waxing have been found to extend the shelf-life of citrus fruit by reducing radiation-induced peel damage and increasing the radiation sensitivity of infecting *micro-organisms*.

See also Codes of practice; Combination treatment; Fruit and vegetables; Grapefruit; Insect disinfestation; legislation; Lemon; Lime; Orange.

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Clam *see* Seafood.

Climacteric *see* Ripening and senescence.

Clostridium botulinum – general

The various types of *Clostridium botulinum* are all Gram-positive rod-shaped *bacteria* that form spores and are obligately anaerobic. The disease botulism is caused by protein neurotoxins that are specific proteases and that are secreted into a food during growth.

There are seven currently recognized types that produce antigenically-distinct *toxins* (Crowther and Baird-Parker, 1983). These are coded types A, B, C, D, E, F and G. An important distinction between the types is whether or not they are proteolytic, as in the following grouping:

Group I proteolytic – A, B or F toxins
Group II non-proteolytic – B, E or F toxins
Group III non-proteolytic – C or D toxins
Group IV weakly or non-proteolytic and non-saccharolytic – G toxin.

Groups I and II strains cause human botulism. Group III strains cause botulism in birds and animals. Group IV strains are rare and not important causes of human botulism.

Another important distinction between the strains is their minimal temperatures for growth. These are 12°C, or above, for most the proteolytic strains that cause human botulism (Group I), but as low as 3.3°C for some of the non-proteolytic strains in Group II.

Reference

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Clostridium botulinum – proteolytic, types A and B

General

Type A strains of *C. botulinum* are the types most often associated with human botulism and predominantly result from the survival of spores, and their subsequent outgrowth, in incorrectly 'home-sterilized' *vegetables*. They are proteolytic, strictly anaerobic spore formers whose spores are relatively heat-resistant. Thermal processes, e.g. as employed in the canning industry for the sterilization of 'low acid' (i.e. high pH) and high water activity foods, are therefore designed to inactivate them by a factor of at least 10^{12} fold. Most commercial practices aim to achieve considerably more than this.

Radiation resistance

The thermal processing industries have long experience, and a good record of safety, with respect to *C. botulinum*. This has derived from a requirement for at least a 10^{12} fold inactivation of type A spores. It has come to be accepted that any alternative process for the sterilization of low acid/high water activity foods must meet equivalent criteria.

Unfortunately spores of Group I *C. botulinum* strains are amongst the most radiation resistant spores known, with *D-values* of types A and B spores reported between about 1.1–3.3 kGy, in water or buffers (Roberts and Ingram, 1965; Grecz, 1965), and up to 3.7 kGy in food products such as canned *chicken, pork, bacon, ham, beef, corned beef, sausages* and *fish* (Anellis *et al.*, 1965, 1967, 1969, 1972, 1975, 1977, 1979). In addition, there are long 'shoulders' on inactivation curves, sometimes reported as up to nearly 10 kGy in length, before exponential inactivation kinetics commence (Goldblith, 1971). Consequently, doses of up to 35 and 45 kGy are necessary to achieve 10^{12} fold kill according to the products and conditions of irradiation. For many foods, even if irradiated at sub-zero temperatures and with *oxygen* rigorously excluded, the organoleptic effects of such high doses are unacceptable.

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Clostridium botulinum – non-proteolytic, types B and E

General

The seven types of *Clostridium botulinum* that may produce neurotoxins in foods include the non-proteolytic type E and non-proteolytic types of B strains. These are of special concern because of their ability to multiply at chill food temperatures, down to just above 3°C. Type E is a common contaminant of *fish*. As with all the *C. botulinum* types, the organisms are strict anaerobes and form heat-resistant spores. However, spores of the low-temperature-growing strains are far less heat tolerant than those of the higher-temperature, proteolytic types.

Radiation resistance

The *D-values* of *C. botulinum* type E spores irradiated in water ranged from 0.8 to 1.6 kGy. Spores irradiated in *beef* stew, at ambient temperature, had a *D-value* of 1.37 kGy (Schmidt *et al.*, 1962).

There has been concern that irradiation of *seafoods*, e.g. to delay spoilage, may allow survival of *C. botulinum* type E spores and therefore increase shelf-life but, at the same time, increase risk. It has therefore often been recommended that the radiation doses applied for spoilage control of such foods should be limited so as to ensure that some of the normal competitive flora remain viable. For example, in order to avoid the possibility of growth from *C. botulinum* E spores in *fish* and *seafoods*, and *toxin* formation prior to obvious spoilage, it was proposed that a maximum dose of 2.5 kGy should be used, so as to ensure that some of the competitive flora remain viable, and that storage should in any case be below 5°C (Lewis, 1984).

Similar studies have shown that when chicken skin was moistened and inoculated with spores of *C. botulinum* type E prior to γ-irradiation at a dose of 3 kGy, *C. botulinum* survivors could not compete with the surviving natural flora during subsequent incubation at 10 and 30°C. Spoilage off-odours were observed prior to *toxin* formation (Firstenberg-Eden *et al.*, 1983).

References

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Cobalt-60 *see* Radionuclide.

Cocksackie virus *see* Viruses.

Cocoa beans

For insect disinfestation, the recommended dose is less than 1 kGy. To increase storage life by control of microbial growth, the recommended dose is 3–5 kGy.

Insect disinfestation

Significant losses of cocoa beans can be caused by *insect* pests during storage. The use of irradiation to control *insect* infestation offers an alternative to existing methods such as chemical fumigation. *Packaging* to prevent reinfestation is vital.

Storage pests that affect the cocoa industry include *Cadra cautella*, *Lasioderma serricorne*, *Araecenis fasciculatus* and *Tribolium casteneum*. In a simulated bulk infestation of these *insects*, the treatment required to attenuate their development was 0.4–0.8 kGy (Amoaka-Atta, 1979). Although the lower dose limit arrested development, it did not prevent feeding damage to the beans during the 4 weeks post-irradiation. The upper limit of 0.8 kGy was recommended, since 100% mortality was achieved within 5 days post-irradiation.

The feasibility of using *gamma irradiation* to disinfest cocoa beans for export from Malaysia has been reported (bin Muda *et al.*, 1991). A 100% mortality of the insects, *Tribolium casteneum*, *Oryzaephilus surinamensis* and *Lasioderma serricorne*, was achieved with a dose of 1 kGy, by 12–18 days post-irradiation. The use of woven polypropylene *packaging* material was found to afford good protection against *insect* damage.

Microbial decontamination

Mould infection of cocoa beans can cause tainting of prepared cocoa beans that can lead to *off-flavours* in chocolate products; *toxin* formation can cause a health hazard.

Radiation doses of the order of 5 kGy have been shown to suppress *mould* growth depending on the microbiological quality of the beans, storage temperature and relative humidity (Stegeman and van Kooij, 1980; Restiano *et al.*, 1984; bin Muda *et al.*, 1991). No adverse effects on the chemical or organoleptic properties of the finished products, made from irradiated cocoa beans, were demonstrated (Takyi and Amuh, 1979; Stegeman and van Kooij, 1980; Appiah *et al.*, 1982; bin Muda *et al.*, 1991).

A *combination treatment* of heat and radiation is effective in inactivating *moulds*. A combination of a dose of 1 kGy, followed by a dry heat treatment of 90°C, significantly decontaminated inoculated beans at 80% relative humidity (Amoaka-Atta *et al.*, 1981). Alternatively, treatment of beans with a combination of moist hot air (30 min at 80°C and >85% RH), and *gamma radiation* at 4 kGy, was recommended (Appiah *et al.*, 1982).

Irradiation of cocoa powder is reported to adversely affect the *flavour* of the final product (Grunewald and Munzner, 1972). A dose of 5 kGy, appropriate for microbial decontamination, could only be used under a vacuum or in an inert atmosphere. The sensitivity of the powder to irradiation increased with fat content.

Potential application

Legal clearance for the irradiation disinfestation of cocoa beans is given in some countries including Syria, Cuba, Israel and Thailand (see Table 10, page 86). The *economic* feasibility of using irradiation to reduce post-harvest losses caused by *insect* infestation and *mould* contamination, in Ghana, has been considered (Nketsia-Tabiri *et al.*, 1993). In Mexico and Cuba, irradiation of cocoa powder is permitted (see Table 10).

See also Insect disinfestation; Legislation.

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Coconut

Insect disinfestation of desiccated coconut and copra (dried coconut meat) by gamma radiation has been investigated (Manoto *et al.*, 1991). Disinfestation of the copra beetle (*Necrobia rufipes*) requires a dose of 0.5 kGy. At this dose, taste and odour are reported to be unchanged (Anon, 1991).

A treatment in the range 4.5–6 kGy is needed to eliminate *Salmonella enteriditis* from coconut. Detrimental sensory effects were evident at this dose level (Ley *et al.*, 1963).

See also Legislation.

References

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Codes of practice

Codex

- Codex Alimentarius Commission (1984) 'Codex General Standard for Irradiated Foods' and 'Recommended International Code of Practice for the Operation of Radiation Facilities used for the Treatment of Foods' CAC/Vol. XV Edition 1, Rome.
- Codex General Standard for the Labelling of Prepackaged Food (CODEX STAN 106–1985 as amended in 1991).

International Consultative Group on Food Irradiation

The following codes of practice are published by the ICGFI, International Atomic Energy Agency, Vienna:

- Code of Good Irradiation Practice for Insect Disinfestation of Cereal Grains. ICGFI Document No. 3, Vienna, 1993.
- Code of Good Irradiation Practice for Prepackaged Meat and Poultry (to control pathogens and/or extend shelf life). ICGFI Document No. 4, Vienna, 1991.
- Code of Good Irradiation Practice for the Control of Pathogens and other Microflora in Spices, Herbs and other Vegetable Seasonings. ICGFI Document No. 5, Vienna, 1991.
- Code of Good Irradiation Practice for Shelf-life Extension of Bananas, Mangoes and Papayas. ICGFI Document No. 6, Vienna, 1991.
- Code of Good Irradiation Practice for Insect Disinfestation of Fresh Fruits (as a quarantine treatment). ICGFI Document No. 7, Vienna, 1991.
- Code of Good Irradiation Practice for Sprout Inhibition of Bulb and Tuber Crops. ICGFI Document No. 8, Vienna, 1991.
- Code of Good Irradiation Practice for Insect Disinfestation of Dried Fish and Salted and Dried Fish. ICGFI Document No. 9, Vienna, 1991.
- Code of Good Irradiation Practice for the Control of Microflora in Fish, Frog Legs and Shrimps. ICGFI Document No. 10, Vienna, 1991.

UK food industry

- Food & Drink – Good Manufacturing Practice: A guide to its responsible management, (3rd edn), Institute of Food Science and Technology (IFST), 1991.

The American Society for Testing and Materials

The ASTM, Philadephia, PA, publishes a number of guidelines relating to dosimetry and the food irradiation process, including:

- E1204 – Practice for the Application of Dosimetry in the Operation of a Gamma Irradiation Facility for Food Processing.
- E1261 – Guide for the Selection and Application of Dosimetry Systems for Radiation Processing of Food.
- E1431 – Practice for Dosimetry in Electron and Bremsstrahlung Irradiation Facilities for Food Processing.
- F1355 – Guide for the Irradiation of Fresh Fruits for Insect Disinfestation as a Quarantine Treatment.
- F1356 – Guide for the Irradiation of Fresh and Frozen Red Meats and Poultry (to control Pathogens).

Codex Alimentarius *see* Codes of practice.

Codling moth *see* Insect; Insect disinfestation.

Coffee beans

Irradiation can be used for *insect disinfestation* of coffee beans (Manoto *et al.*, 1991; Soemartaputra *et al.*, 1991). A radiation dose in the range of 0.6–0.9 kGy gave a 100% mortality of the coffee bean weevil (*Araecerus fasciculatus*). The treatment had no detectable effect on caffeine, fat, moisture content, or pH of the irradiated beans. The *flavour* or aroma of coffee beans irradiated at 0.5 kGy was unaffected (Dias *et al.*, 1978).

In Israel, irradiation of coffee beans for the purpose of disinfestation is permitted up to an overall average dose of 1 kGy (see Table 10, page 86).

See also Insect disinfestation; Legislation.

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Coleoptera *see* Insects.

Colour

Irradiation induces colour changes in both fresh and cured *meats*. The effect of irradiation on the colour of *meat* is reviewed by Diehl (1983). At doses above approximately 1.5 kGy, and in the presence of *oxygen*, oxidation of the purple meat pigment, myoglobin, to brownish-grey metmyoglobin occurs. Following irradiation in the absence of air, or at higher radiation levels (above approximately 10 kGy), a bright red colour is observed. This is a reduced denatured myoglobin that is easily oxidized by oxygen to the usual brownish-grey pigment (Urbain, 1986). Similarly, irradiated *chicken* and *pork* may develop a pink discolouration after relatively low doses of irradiation, as metmyoglobin is reduced to myoglobin by *free radicals*.

Polyphosphates, which may be added to control drip in irradiated *meat*, also help to maintain colour. It has been recommended that *meat* is irradiated in vacuum packages; subsequent exposure of the retail cut to *oxygen* returns the cut to its normal red colour (Urbain, 1986). Discolouration induced by irradiation is more important for *beef* and *lamb*; *pork*, veal and *chicken* are less sensitive to change.

Colour changes occur in irradiated *fish*. Colour loss is observed in irradiated salmon and trout, at doses as low as 1 kGy (Urbain, 1986). A greater loss of colour is observed in *shrimps* of the *Penaeidae* family, compared with *shrimps* of the *Crangonidae* family, because of differences in radiation sensitivities of their carotenoid pigments (Snauwaert *et al.*, 1973). Irradiation of lobster and *shrimp* results in melanosis – 'black spot'. Blanching in hot water prior to irradiation is effective in controlling this problem (Nickerson *et al.*, 1983).

Colour changes in *fruits* and *vegetables* are rarely a limiting factor. If the effect of irradiation is to delay *ripening*, uneven colour development may occur in *fruits*, e.g. *tomatoes*. Irradiation may exacerbate browning in *bananas*. Browning of the inner buds of irradiated *garlic* and *onions* is common feature. After-cooking darkening, in irradiated *potato* tubers, has been correlated with increased levels of polyphenols and chlorogenic acid in tuber tissue after irradiation (Thomas, 1983). Greening, due to chlorophyll accumulation, was delayed in irradiated *potatoes*.

See also Proteins.

References

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Combination treatment

The benefits of treating food with a combination of irradiation (doses below 10 kGy) and heat, low temperature, modified-atmosphere packaging or conventional preservatives are recognized (IAEA, 1981; Campbell-Platt and Grandison, 1990; Farkas, 1990). By combining irradiation with other preservation technologies, a lower radiation dose can be used to achieve the required objective and this preserves food product quality. However, the *economic* implications of combination treatments need to be considered.

Modelling is increasingly used to predict the responses of *micro-organisms* to combinations of antimicrobial agents and processing methods. Databases developed so far mostly cover the effects of parameters, such as temperature, pH value, water activity, and some preservatives, on microbial growth and survival, and also on inactivation by heat. As radiation processing of foods increases, it will be important to include the effects of irradiation in these databases.

Irradiation combined with heat

The overall effectiveness of combination treatments will depend on the microflora present in the product and the specific sequence of the individual treatments (Farkas, 1990). In addition, the time elapsed between the two treatments is important.

Simultaneous application of heat and radiation is an effective combination for inactivating microbial cells (thermoradiation). A combination of heat and *ionizing radiation* for *meat* products and *vegetables* gave sterilized products of satisfactory microbiological, nutritional and sensory quality (Hozova and Sorman, 1991). Development of a heat-irradiation combination treatment to produce shelf-stable *mushrooms* in brine has been described (Minnaar and McGill, 1992).

Heat treatment before irradiation is an effective treatment for the inactivation of *moulds*. There are many examples of the use of a mild heat treatment, followed by a low radiation dose, for fresh *fruits* and *vegetables* (Farkas, 1990). Shelf-life is extended and product quality preserved (see Table 2).

While the effect of heating before irradiation is additive or slightly more than additive, *ionizing radiation* applied before heating is strongly *synergistic* in the inactivation of bacterial spores (Gombas and Gomez, 1978). The effect is dependent on dose rate (Fisher and Pflug, 1977) and is enhanced, reversibly, by pretreatment of the spores at low pH values (Stegeman *et al.*, 1977). The *micro-organisms* surviving radiation treatment of *spices* appear to be heat sensitized, and more easily destroyed by normal heat processing of spice-containing food than *micro-organisms* of untreated, or fumigated *spices* (Farkas, 1988).

High temperatures applied before radiation sensitize insects to radiation (Tilton and Brower, 1985). A combination treatment would allow the use of a low radiation dose to treat stored products.

Irradiation combined with low temperatures

The functions of chilling are to suppress microbiological spoilage, interfere with *insect* metabolism, and inhibit autolysis, oxidation processes, etc. *Vitamin* loss is reduced. The value of combined treatments of ionizing energy and chilling has been demonstrated. Examples of the application of irradiation and refrigeration to extend shelf-life and preserve product quality are given in Table 3.

Table 2 Examples of heat and irradiation combination treatment of foods.

Food	Heat treatment	Irradiation treatment	Result	Reference (see product section)
Papaya	49°C/20 min	0.75 kGy	Shelf-life extension	Moy and Nagai (1985)
Fig	Hot water dip 50°C/5 min	1.5 kGy	Delayed fungal spoilage	Padwal-Desai *et al.* (1973)
Grape	Hot water dip 50°C/5 min	1.0 kGy	Delayed incidence of fungal spoilage	Padwal-Desai *et al.* (1973)
Mango	Hot water dip 50°C/10 min	0.25–0.75 kGy	Reduced incidence of fungal infection; delayed senescence	Thomas (1986)
Banana	50°C/5 min moist heat	0.25–0.35 kGy	Delayed ripening and reduction of stem end rot	Padwal-Desai *et al.*(1973)
Avocado	46°C/10 min	0.025 kGy + PVC shrink foil wrapping	Delayed and reduced spoilage; preservation of fruit quality	Ang *et al.* (1986) Karmelic *et al.* (1985)
Lime	45°C/5 min	0.5 kGy	Improvement in storage life	Nyambati and Langerak (1982)
Pear	45°C/5 min	0.5 kGy	Prevention of rotting of unripe fruit	Stegeman (1982)
Tomato	45°C/ 5 min	1.25 kGy	Eliminated fungal spores without affecting fruit quality	Stegeman (1982)
Dried date	40°C/48 h (radiation first)	0.7 kGy	Control of *Ephestia cautella*	Ahmed *et al.* (1986)
Chapatti, bread slices	Dry heat 65 min/ 35 min (radiation first)	0.5 kGy	Reduced incidence of mould infection; extended shelf-life	Padwal-Desai *et al.* (1973)

Irradiation is unique in its ability to inactivate non-sporing pathogenic *bacteria* in the frozen state. Such organisms may be associated with frozen food of animal origin, e.g. *poultry, meat, seafood.* This is accomplished without changing the physico-chemical and sensory characteristics of the food. The combination of freezing and irradiation is useful for such foods, which may develop *off-flavours* and off-odours when given appropriate radiation doses at temperatures above freezing (CAST, 1989). The bactericidal effect of irradiation is reduced at *temperatures* below freezing and this must be taken into account when calculating the necessary dose for treatment.

Table 3 Examples of irradiation combined with chilling to extend shelf-life.

Food	Combination treatment	Reference (see product section)
Orange, lemon	0.75–1 kGy 7°C storage	Moy and Nagai (1985)
Strawberry	1–3 kGy 4°C storage	Thomas (1986)
Grapefruit	0.05 kGy 5 days, 1.1°C	von Windeguth (1992)
Fish (hake)	3.3 kGy 3°C storage	Kairiyama *et al.* (1990)

Irradiation combined with modified atmospheres

Most *applications* of food irradiation will involve the irradiation of the food product in its final package. This prevents reinfestation of the product by *insects* or *microorganisms.* Careful choice of *packaging* materials can provide a modified atmosphere in which the food is irradiated and subsequently stored.

The shelf-life of fresh *fruits* and *vegetables* can be extended by using low or medium doses of irradiation and a modified atmosphere (see Table 4). Respiration rates, and hence deterioration, are slowed down by elevated levels of carbon dioxide and reduced *oxygen* levels in the packages (Campbell-Platt and Grandison, 1990). In addition, modified atmosphere packaging and irradiation can be used to extend the shelf-life and preserve the sensory properties of irradiated *chicken* and *pork* (see Table 4).

Table 4 Examples of irradiation combined with modified atmospheres and packaging to extend shelf-life of foods.

Food	Combination Treatment	Reference (see product section)
Sweetcorn	0.5–1 kGy shrink wrapped cold storage	Deak *et al.* (1987)
Asparagus	1–1.5 kGy PVC wrapping cold storage	van der Linde (1982)
Prepacked vegetables	1 kGy polythene packaging	Langerak (1978)
Pork	25% CO_2: 75% N_2; 1.75 kGy	Grant and Patterson (1991)
Chicken	20% CO_2: 80% O_2; 1 kGy	Grandison and Jennings (1993)

The beneficial effects of vacuum packaging in combination with irradiation have been demonstrated for *meat* and *fish*. *Oxygen* is required for growth of some spoilage organisms. In addition, *oxygen* reacts chemically with some constituents in foods, e.g. fats, causing oxidation and *off-flavours* in *lipid*-containing foods (CAST, 1989). Storage under nitrogen prevents radiation-induced *vitamin* loss (Diehl, 1991). Vacuum packaging, in combination with irradiation extends shelf-life, and preserves the sensory and nutritional quality of food. Generally, *bacteria* are more sensitive to radiation in the presence, rather than in the absence, of *oxygen* (Figure 11, page 105), although exceptions have been reported (Table 18, page 131).

Other combination treatments

Spices are known to have useful antimicrobial properties. Combinations of irradiation treatments with *spices* in processed foods have been shown to have beneficial effects (Campbell-Platt and Grandison, 1990).

The combination of irradiation with preservatives, such as potassium sorbate and potassium metabisulphite, has been investigated. Dipping *lime* fruits in potassium metabisulphite, and irradiating with a low dose of 0.25 kGy, was found to have a *synergistic* effect (Nyambati and Langerak, 1982). A combination of potassium sorbate, and a dose of 1 kGy, for cod, gave a longer shelf-life than either treatment alone (Licciardello *et al.*, 1984).

In vacuum-packed *pork*, low dose irradiation, in combination with a reduction in water activity or pH reduction, was an effective method of extending shelf-life (Banati *et al.*, 1991; IAEA, 1993). The shelf-life of semi-dried *fish* can be extended by a combination of salting, drying and irradiation (IAEA, 1993).

A combination of irradiation and calcium treatment prevented softening and extended the shelf-life of *pears* and *apples* (Kovacs *et al.*, 1988). Use of *packaging* or waxing of *fruits*, such as *oranges*, to extend the shelf-life and improve the sensory quality of irradiated produce, has been successful (Barkai-Golan, 1992).

The application of high hydrostatic pressure causes spores of *bacteria* to germinate (Gould and Sale, 1970), thus reducing their radiation resistance. For example, the use of hydrostatic pressure above 500 bar, applied to food containing spores of *Bacillus pumilis*, leads to their germination, thus increasing their sensitivity to radiation (Wills, 1974; 1975).

Nutritional effects

The nutritional effects of combining irradiation with other treatments on a range of foods have been reviewed by Diehl (1991). In general, combination treatments allow the use of lower doses of irradiation to achieve the required objective. This will have the effect of minimizing adverse nutritional effects.

See also Modelling; Nitrite reduction; Nutrition; Spores – sensitization to heat.

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Comet assay

The comet assay gives an indication of fragmentation of DNA within a cell, and can be used therefore to detect such damage, which is caused by irradiation. The procedure involves first treating tissue samples to lyse cells so that, when subjected to agarose gel electrophoresis, their DNA is forced out to give a characteristic comet-shaped pattern (Muller *et al.*, 1994). This can be visualized by staining with ethidium bromide or, better still, with silver, and by subsequent microscopic examination and density tracing. The extent of the comet's 'tail' is a function of irradiation-induced damage to the DNA. The technique is useful for foods in which DNA has not been damaged by means other than irradiation. For instance, it is of no value for heated foods because heating causes DNA fragmentation too (Delincée, 1993).

See also Detection; DNA damage.

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Commercial applications

Food irradiation is approved in 36 countries, but only certain countries use irradiation on a small-scale commercial basis (see Table 5). Each year approx. half a million tonnes of food and ingredients are irradiated worldwide (ICGFI, 1991). Approximate tonnages of food irradiated by individual countries is given in Diehl (1990). Increases in the tonnages of *spices* and vegetable seasonings that have been irradiated commercially, from 1987 to 1992, are shown in Figure 13, page 145.

See also Consumer attitudes; Economics; Legislation; Market trials.

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Composite foods

The effects of irradiation on composite meals, such as pizza, dishes containing sauces, coated *meat* or *poultry* products, will depend on the individual components. *Combination treatments* of composite meals composed of a number of different food items have been investigated (FAO/IAEA, 1993). An optimal treatment for each component is needed. Interaction between different meal components and the *packaging* may occur during the treatment.

See also Ready meals.

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Table 5 Countries with irradiation facilities available for commercial food processing (July 1994). Published with permission of the International Atomic Energy Agency, 1994.

Country	Location (starting date for food irradiation)	Products
Algeria	Mascara*	Potatoes
Argentina	Buenos Aires (1986)	Spices, spinach, cocoa powder
Bangladesh	Chittagong (1993)	Potatoes, onions, dried fish
Belgium	Fleurus (1981)	Spices, dehydrated veg., deep frozen foods
Brazil	Sao Paulo (1985)	Spices dehydrated veg.
Canada	Laval (1989)	Spices
Chile	Santiago (1983)	Spices, dehydrated veg., onions, potatoes, poultry meat
China	Chengdu (1978)	Spices and veg. seasonings, Chinese sausage, garlic
	Shanghai (1986)	Apples, potatoes, onions, garlic, dehydrated veg.
	Zhengzhou (1986)	Garlic, seasonings, sauces
	Nanjing (1987)	Tomatoes
	Jinan (1987)	Not specified
	Lanzhou (1988)	Not specified
	Beijing (1988)	Not specified
	Tienjin (1988)	Not specified
	Daqing (1988)	Not specified
	Jianou (1991)	Not specified
Cote D'Ivoire	Abidjan*	Yams, cocoa beans
Croatia	Zagreb (1985)	Spices, rice, food ingredients
Cuba	Havana (1987)	Potatoes, onions, cocoa beans
Czech Republic	Prague (1993)	Spices, dry food ingredients
Denmark	Riso (1986)	Spices
Finland	Ilomantsi (1986)	Spices
France	Lyon (1982)	Spices
	Paris (1986)	Spices, veg. seasonings
	Nice (1986)	Spices
	Vannes (1987)	Poultry (frozen deboned chicken)

Table 5 continued

Country	Location (starting date for food irradiation)	Products
France (cont.)	Marseille (1989)	Spices, veg. seasonings, dried fruit, frozen frog legs, shrimp, poultry (frozen deboned chicken)
	Pouzauges (1991)	Not specified
	Osmanville	Not specified
	Sable-sur-Sarthe (1992)	Camembert
Hungary	Budapest (1982)	Spices, onions, enzymes
India	Bombay*	Spices
	Nasik*	Onions
Indonesia	Pasar Jumat (1988)	Spices
	Cibitung (1992)	
Iran	Tehran (1991)	Spices
Israel	Yavne (1986)	Spices, condiments, dry ingredients
Japan	Shihoro (1973)	Potatoes
Korea, Rep.	Seoul (1986)	Garlic powder, spices and condiments
Mexico	Mexico City (1988)	Spices, dry food ingredients
Netherlands	Ede (1981)	Spices, frozen products, poultry,dehydrated veg., rice, egg powder, packaging material
Norway	Kjeller (1982)	Spices
Poland	Warsaw (1984)	
	Wlochy (1991)	
	Lodz (1984)	
Serbia	Belgrade (1986)	Spices
South Africa	Pretoria (1968)	Potatoes, onions
	Pretoria (1971)	Fruits
	Pretoria (1980)	Spices, meat, fish, chicken, fruits, spices
	Tzaneen (1981)	Onions, potatoes, processed products
	Kempton Park (1981)	Fruits, spices potatoes
	Mulnerton (1986)	Fruits, spices
Thailand	Patumthani (1989)	Onions, fermented pork sausages, enzymes, spices
Ukraine	Odessa (1983)	Grain
UK	Swindon (1991)	Spices

Table 5 continued

Country	Location (starting date for food irradiation)	Products
USA	Rockaway, NJ (1984)	Spices
	Whippany, NJ (1984)	Spices
	Irvine, CA (1984)	Spices
	Gainsville, FL (1993)	Strawberries, poultry
	Ames, IA (1993) *	Not specified
	Mulberry, FL (1992)	Fruits, vegetables, poultry

* denotes facilities under construction or planned

Conductivity *see* Impedance and conductivity.

Consumer attitudes

Consumer attitudes to food irradiation are perceived as a crucial issue. Use of the treatment as a commercial food process will depend on acceptance by consumers. Analysis of attitudes, which vary according to country, national traditions and political climate, have been extensively reviewed (Bruhn, 1995; Feenstra and Scholten, 1991; Bord, 1991; Loaharanu; 1993).

Consumer organizations

In the 1980s, the major concerns of consumer organizations included *safety*, *nutrition*, *detection* and *labelling* of irradiated food. There were fears that the process would be used to upgrade low-quality products. In 1987, the International Organization of Consumers Unions (IOCU), representing consumer organizations in member states across Europe, Asia and Latin America, adopted a resolution on food irradiation calling for a worldwide moratorium on the subject (Feenstra and Sholten, 1991). At the same time, a number of consumer organizations, including the London Food Commission and the National Coalition to Stop Food Irradiation, questioned the integrity and competence of food irradiation promoters. Health and environmental pressure groups opposed the introduction of the technology. In addition, the media emphasized concerns about food irradiation. Anti-food irradiation groups were successful in influencing legislation, with major food companies taking anti-irradiation stances (Pszczola, 1990; Satin, 1993).

Opposition to food irradiation still exists. Recent actions by opponents of food irradiation include picketing, making inflammatory demands, and pressurizing legislation (Pszczola, 1990; Satin, 1993). However, the IOCU has taken a more independent and unbiased approach to food irradiation. In a joint IOCU/International Consultative Group on Food Irradiation seminar on food irradiation and consumers (IAEA, 1993), a number of recommendations were agreed on areas including *applications*, trade and environmental implications, regulation and enforcement, consumer acceptance and *labelling*.

General public

It is recognized that attitudes of consumer organizations can strongly influence consumer opinions (Taylor, 1989). Consumer resistance to food irradiation appears to be linked to the growth in popularity for *additive*-free, minimally processed foods, and environmentally acceptable food processing techniques. However, recent consumer surveys in the USA indicated that concern about irradiation is less than other food-related issues, such as food additives, pesticides and animal drug residues (Resurreccion *et al.*, 1995). Concerns about the use of irradiation to treat foods appear to centre on the safety of the process. This is often linked to the fear and confusion about radiation itself and the lack of understanding of the process. Providing science-based information about food irradiation leads to positive consumer attitudes (Bruhn, 1995).

Consumer surveys, carried out in the USA and UK in the 1980s, demonstrated that the majority of people did not have prior knowledge of the treatment. In America, approximately 25% of people were aware of food irradiation in the mid-1980s, with this percentage increasing to over 70% in the early 1990s (Bord, 1991; Resurreccion *et al.*, 1995). Opinion polls reflect the level of awareness and quality of information provided. Information about the process tends to promote acceptance. The results of nationwide opinion polls and market trials in a number of countries are summarized by Loaharanu (1993) and Bruhn (1995).

Manufacturers and retailers

Attitudes of manufacturers, producers and retailers to food irradiation are analyzed by Satin (1993). Despite the recognition that irradiation could be used to improve food safety, and increase the shelf-life of certain products, there is concern about the image presented to consumers by irradiated food. Lack of consistency in regulations and controls, both in Europe and worldwide, are a disincentive. However, it has been argued (Sivinski, 1985) that consumer acceptance can best be developed by the food industry.

Changing attitudes

Labelling of irradiated foods is a key issue with consumers. There appears to be a marked influence of informative *labelling* on consumers' willingness to buy irradiated food. *Labelling* to provide identification is not sufficient. Information that describes the purpose of treatment promotes consumer acceptability, e.g. for irradiated chicken, the words 'treated by irradiation to control Salmonella and other foodborne bacteria' (Pszczola, 1993). Additional consumer education and information needs to be available in the place where the product is marketed (Corrigan, 1993).

The consumers' willingness to buy irradiated foods appears to be higher than expected on the basis of their non-acceptance (see Table 11, page 98). There were successful market trials of irradiated *mangoes* and *papayas*, in supermarkets in the USA, in 1986 and 1987 (Satin, 1993). The sales of irradiated *strawberries* (Marcotte, 1992) and *poultry* (Pszczola, 1993), in the United States, supports this view. In France, *strawberries* were irradiated and sold with the label 'Protégé par ionisation' (protected by ionization). The *strawberries* were sold side-by-side with untreated ones but at a 30% extra price, and a freshness guarantee of 4 days. Turnover of irradiated *strawberries* equalled that of the untreated *fruit* (Laizier, 1987).

In South Africa, acceptance has been attributed to consumer concern about food-borne illness (Goodburn, 1990). Irradiation is permitted to treat Rooibos Tea to prevent salmonellae poisoning, which has been associated with the product. In Germany, where food irradiation is not permitted, the strength of the Green Party has hardened views against the process.

There is evidence to suggest that if irradiated food products offer clear advantages, and if science-based information about the process is readily available, many consumers would be ready to buy irradiated food (Bruhn, 1995).

See also Labelling; Legislation; Market trials.

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Containers *see* Packaging.

Control of food irradiation

General

Strict control measures for food irradiation facilities are necessary to guarantee the quality and safety of irradiated food (Pothisiri, 1989). Government authorities need to ensure that manufacturers, distributors, irradiation plant operators and retailers comply with national and international standards. Furthermore, proper regulatory control, inspection during and after irradiation, and good irradiation practice facilitate international trade in irradiated food.

Some of the legal requirements stipulated by food irradiation regulations cannot be enforced by authorities (Ehlermann, 1993). For example, the overall average, and minimum and maximum doses, can only be established from records of measurements made in the irradiation plant. In addition, it is not easy to distinguish irradiated from non-irradiated products. Identification *per se* does not prove adherence to legal dose limits for a particular food. Thus, process control at the facility, involving documentation at all key stages of the irradiation process, is essential. Only reliable inspection of these records, at the irradiation facility, can reveal the absorbed radiation dose received by the product and render *labelling* of irradiated food meaningful (Ehlermann, 1993).

Codex standard

Adoption of the Codex standard (Codex, 1984) by operators of food irradiation facilities is essential. This states that a food irradiation facility must meet requirements of safety, efficacy and good hygienic practice of food processing. Irradiated foods should be accompanied by shipping documents identifying the irradiator, date of treatment, lot identification, dose and other details of treatment. Process control at an irradiation facility does not only involve defining operational parameters, such as radiation dose, maximum and minimum dose ratio, but may also cover aspects such as *temperature*, atmosphere and *packaging* of the food product.

Process control

Process control of food irradiation is recognized as including (Anon, 1992):

- compliance with Codex General Standard and Codex Recommended International Code of Practice;
- inspection, licensing and registration of all irradiation facilities used for the treatment of foods;
- adherence to good manufacturing practice and good radiation processing;
- accurate dosimetry traceable to national and international standards of absorbed dose;
- dose mapping for each product type and loading pattern;
- written standard operation procedures specifically for each irradiation facility;
- written protocols for each application and food type;
- adequate documentation to follow treated goods;
- identification of individual consignments and adequate records to enable follow-up of complaints or enquiries;
- quality standards for food to be irradiated and procedures for inspection and testing on receipt, before and after irradiation;
- training program for operation staff;
- a quality assurance programme.

Process control needs to include a quality control programme, not just for irradiation processing *per se*, but for the complete chain, including food production, storage, transport and retail sales (Pothisiri, 1989).

Guidelines

The International Consultative Group on Food Irradiation (ICGFI) has initiated the establishment of an 'International Register of Food Irradiation Facilities' to assist member countries in the control of irradiated foods in international trade (Loaharanu, 1990). Guidelines for preparing regulations for the control of food irradiation facilities are published by the International Atomic Energy Agency (ICGFI Document No. 1, 1991).

Guidelines for good manufacturing practice and good radiation practice for a number of foods have been prepared by the ICGFI. These guidelines emphasize that, as with all food processing, effective quality control systems need to be installed and monitored at critical control points (*HACCP*) in the irradiation facility. Foods should be handled, stored and transported according to good manufacturing practice, before, during and after irradiation. Only foods meeting microbiological criteria and other quality standards should be accepted for irradiation. A training programme, for operators of irradiators that treat food commercially, and for food inspectors, is available under the auspices of the ICGFI.

Guidelines for irradiated food, with reference to UK legislation are available (IFST, 1991). These cover food irradiation facilities and control of the process, food quality, *application* of the process, *re-irradiation*, import and export of irradiated food and *labelling*.

See also Codes of practice; Detection; Dosimetry; Facilities; HACCP; Legislation.

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Convenience foods *see* Composite foods; Ready meals.

Cost *see* Economics.

Cranberry *see* Berries.

Crustacea *see* Seafood.

Cucumber

Cucumbers are sensitive to radiation damage. Radiation-induced yellowing and softening are observed, with textural changes occurring at doses as low as 0.5 kGy (Thomas, 1988). Softening of the product is associated with the altered solubility characteristics of pectic substances (Howard and Buescher, 1989).

See also Pectin and cellulose; Texture.

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Curie

The curie (Ci) is an old unit of *radioactivity*. It was originally defined as the number of disintegrations per second that occur in one gram of radium. The new SI unit of *radioactivity* is the *Becquerel* (Bq).

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{Bq}$$

Currants *see* Dried fruit.

Cyanocobalamin (vitamin B12)

General

The major sources of vitamin B12 are *meats* and especially organs such as liver, kidney and heart. The molecule is a ring structure, composed of four pyrrole residues and containing six conjugated double bonds, and sequestered cobalt, which can exist in three distinct oxidation states. The molecule may be inactivated in the presence of reducing agents but is otherwise relatively chemically stable at the neutral to slightly acidic pH values of most foods. Deficiency of vitamin B12 results in weakness and gastrointestinal disorders. Severe deficiency results in pernicious anaemia.

Radiation sensitivity

Most studies have indicated that little or no loss of vitamin B12 occurs during food irradiation, e.g. in various *seafoods* at doses up to about 4.5 kGy (Brooke *et al.*, 1964); in *pork* irradiated at doses up to about 7 kGy (Fox *et al.*, 1989); and in *poultry*, in a study comparing the nutritional effects of preservation by freezing with sterilization by heat and with sterilization by irradiation (Thayer *et al.*, 1987).

See also Nutrition; Vitamins.

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Cyclobutanone *see* Detection; 2-Dodecylcyclobutanone.

D

Dairy products

Irradiation may be used to control spoilage and pathogenic micro-organisms

Product characteristics

Most of the early research work on the irradiation of milk and dairy products concentrated on the effects of high radiation doses suitable for sterilization (Morré *et al.*, 1978). However, the bacteriological advantages were limited by undesirable changes in sensory quality of the products.

In general, milk and dairy products are very susceptible to radiation-induced *flavour* changes (Diehl, 1983). *Off-flavours* and off-odours, which characterize irradiated dairy products, appear to be due to the milk *protein* fraction producing sulphur compounds and to the *lipid* fraction causing oxidative rancidity.

The threshold value for *off-flavour* production in milk depends on its composition. A threshold of 0.3 kGy or lower is reported for whole liquid milk; in general, skimmed milk and dried milk powders are more resistant (Diehl, 1983). Doses as low as 0.07 kGy have been quoted for whole milk and 0.2 kGy for skimmed milk. Irradiation of pasteurized milk at 0.25 kGy, at room temperature, was found to double the shelf-life at 4°C (Sadoun et al., 1991). There was a loss of up to a 17% in levels of vitamins B1, B2 and A. Irradiation of raw milk at 0.5 kGy did not increase shelf-life significantly.

Threshold values for *off-flavour* development in cheese depend on many factors, including composition and conditions of radiation and storage. For example:

Camembert cheese: 2.5 kGy (Bougle and Stahl, 1993)
Cottage cheese: 0.75 kGy (Jones and Jelen, 1988)
Turkish Kashar cheese: 1.5 kGy (Yuceer and Gunduz, 1980)
Egyptian Ras cheese: 5 kGy (Abdel Baky *et al.*, 1986)
Yogurt: 1.5 kGy (Yuceer and Gunduz, 1980).

Combination treatment

Control of organoleptic changes in irradiated dairy products using low temperatures or anoxia has been examined. Irradiation under nitrogen minimizes *lipid* peroxidation, one of the causes of organoleptic changes (Searle and McAthey, 1989). Combining heat and irradiation to treat dairy products could lower the requirement for both (Morré *et al.*, 1978). However, the *economics* of such treatments are questionable.

There are advantages of *combination treatments* for irradiation-sterilized dairy products suitable for diets of immunosuppressed patients (Dong *et al.*, 1989; Hashisaka *et al.*, 1990). The effect of a dose of 40 kGy, at −78°C, on non-fat dry milk, cheese and dairy desserts, suitable for diets of immunosuppressed patients, was investigated. The acceptability of the product was affected but not the *vitamin* content. Modified atmosphere packaging or antioxidant addition were used to improve the sensory quality of the products.

Potential application

Irradiation is an effective method of destroying pathogenic *bacteria*, such as *Listeria monocytogenes* and *Salmonella*, in Camembert cheese (Bougle and Stahl, 1993). In France, legal permission has been given for the sale of Camembert cheese made from raw milk, in which the overall microbial loads are reduced by exposure to *gamma radiation* with a dose of 2.25–3.5 kGy (Anon, 1993). Radiation processing is considered to be the only practical alternative to meet microbiological standards demanded by some countries for international trade in this product.

Microbial decontamination of ingredients added to dairy products may have commercial potential. Legal clearance for irradiation of cereal flakes for dairy products is given in France (Anon, 1985).

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Dates

The distribution and availability of fresh dates are limited by perishability. The feasibility of improving the market life of fresh dates using irradiation has been studied (Farkas *et al.*, 1974). Variety and developmental stage of dates are important. In general, fruit softening was delayed by low doses in the range 0.1–0.3 kGy, while higher doses, above 2 kGy, stimulated the softening process. Microbial spoilage could be controlled at doses above 0.9 kGy. The shelf-life of irradiated fresh dates was increased with a dose of 2–5 kGy; the eating quality of the *fruit* was not affected.

Reference

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Dates – dried *see* Dried fruit.

DEFT *see* Direct epifluorescent filter techniques.

Dehydroascorbic acid *see* Ascorbic acid.

Density *see* Dose distribution; Facilities.

Detection

General

The development of detection techniques is needed, in order that regulating authorities can determine whether or not a particular food sample has been irradiated. Ideally, determination of actual dose is desirable (Swallow, 1990).

A problem in the development of such techniques has been that the chemical and physical changes brought about in foods, by practical doses of irradiation, are very small, so that very sensitive methods are required. The other key problem is that most of the changes induced by irradiation are not specific to the treatment. Nevertheless, a number of promising approaches have been developed and evaluated. These include chemical, physical and biological methods (reviewed by Bogl *et al.*, 1988; Bogl, 1990; Glidewell *et al.*, 1993).

Methods

The chemical methods rely on the detection of low levels of the products of radiolysis, using conventional methods of analysis, such as gas-liquid chromatography. A key requirement of chemical methods is that the products analysed should be sufficiently distinct, qualitatively and/or quantitatively, from those present in the unirradiated foodstuff. These have therefore included: analyses for low molecular weight *volatiles* generated from fatty acids during the irradiation of lipids, such as acyl cyclobutanones; detection of *o-tyrosine*, generated during the irradiation of *proteins*; detection of changes in *DNA*, in particular single and double strand breaks and chemical modification of bases.

The physical methods include: luminescence, e.g. emission of photons of light, for example on heating an irradiated food, which is particularly relevant to *spices* and other foods; measurement of conductance and/or *impedance*, which change on irradiation of some foods, such as whole *potatoes*; *electron spin resonance* (ESR) to detect *free radicals* in irradiated foods. Whilst ESR is especially applicable to dry rather than wet foods, it has been particularly successful in determining the doses applied to *poultry* by the ESR analysis of bone. Changes in viscosity, which accompany the chain scission of polymers in some foods, form the basis of another physical method of detection.

The biological methods include those based on the direct physiological effect of irradiation on the target foodstuff, e.g. the ability of bulbs and tubers to germinate and initiate growth ('shoot and root'). Biological methods also include indirect ones, e.g. isolation of *micro-organisms* from the food and assessment of the viability, or physiological status, of different types in such a way as to infer whether or not, and to what extent, they have been irradiated. A promising example of this is the DEFT (*direct epifluorescent filter technique*).

Stevenson (1992) reviewed progress in the development of the various methodologies. She concluded that no single method is universally applicable to all foods, but for individual food types, several specific methods are sufficiently reproducible to be valuable, though still with generally only a rough estimate of dose.

See also Carbon monoxide; Chemiluminescence; Comet assay; Direct epifluorescent filter techniques (DEFT); 2-Dodecylcyclobutanone; DNA damage; Electron spin resonance (ESR); Hydrogen; Impedance and conductivity; Photostimulated luminescence; Supercooling; Thermoluminescence; o-Tyrosine; Viscosity; Volatiles.

References

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Direct and indirect action of ionizing radiation

Ionizing radiation inactivates *micro-organisms*, *insects or parasites*, and also affects large and small molecules in foods, by acting directly and indirectly. In direct action, a sensitive ('lethal') target (e.g. the cells' *DNA* in a living organism) is damaged directly by an ionizing particle or ray. In indirect action, the cell is affected by the products of radiolysis, usually of water in most food situations. Products of radiolysis (e.g. including *hydrated electrons*, *hydrogen* and *hydroxyl radicals*, *hydrogen peroxide*, etc.) then diffuse into, or within, the cell before reacting with sensitive target sites (Goldblith, 1971).

Direct action is little affected by the environment of the cell, i.e. by the constituents of a food, and is the predominant cause of the inactivation of *micro-organisms* irradiated in foodstuffs. In contrast, that part of the total inactivation that is caused by indirect action is greatly influenced by the environment. In particular, large amounts of *protein*, *lipid* and the other components in foods, act as traps by reacting with the products of radiolysis. Thus, *micro-organisms* are protected to varying degrees from damage caused by indirect action. Similar protection from damage by indirect action is afforded to small molecules, such as *vitamins*, and to larger molecules, such as individual *enzymes* and *toxins* in foods.

The extent of the protection that can be afforded by the suppression of indirect action in foods is well illustrated by the large reduction in resistance of *micro-organisms* that often occurs when a food is diluted. This is well illustrated by the data in Table 6, which show the approximate halving of the resistance of *Salmonella typhi* and *paratyphi* B that accompanied dilution of crab meat by up to 10-fold in water.

See also DNA damage; Ionization.

Reference

Goldblith, S.A. (1971) The inhibition and destruction of the microbial cell by radiation, in *Inhibition and Destruction of the Microbial Cell*, (ed. W.B. Hugo) London, Academic Press, pp. 285–305.

Direct epifluorescent filter technique (DEFT)

The direct epifluorescent filter technique was first developed and refined by Pettipher *et al.* (1980) for the enumeration of *micro-organisms* in raw *milk*. The technique may be applied to other foods, and usually involves macerating the food with a diluent, if it is a solid, prior to treating a sample with a detergent, and a protease, to remove interfering food debris. The sample is then filtered through a 0.6 μm pore size polycarbonate membrane filter, which retains any micro-organisms present on its upper surface. These may be allowed to multiply to form discrete clumps for some applications. The single micro-oganisms or clumps are stained with acridine orange, which reacts

Table 6 Reduction of radiation-resistance of salmonellae by food dilution (from Goldblith, 1971).

Organism	**D-value (kGy) in crab meat diluted:**					
	Undiluted	**1:3**	**1:4**	**1:5**	**1:7**	**1:10**
S. typhi	0.48	0.46	0.38	0.35	0.32	0.27
S. paratyphi	0.30	0.23	0.21	0.16	0.13	0.12

mainly with ribonucleic acids in the microbial cells in such a way that they fluoresce orange when illuminated with ultraviolet light. A microscopic count can be made, either by eye or automatically.

The technique was adapted for the *detection* of irradiated foods by Betts *et al.* (1988) and Jones *et al.* (1994). The basis of the method is that counts of direct microbial filters are compared with viable, aerobic plate counts, made by conventional means. The former essentially detects all *bacteria*, whether live or inactivated by radiation, whereas the latter detects only viable cells. The difference is therefore a measure of microbial inactivation, which is related to the radiation dose received.

For example, the method was shown to work well when applied to frozen *chicken* meat stored for up to 100 days. With chill-stored (4°C) *chicken* meat, the method was effective during the early stages of storage, but not towards the end of the 10-day shelf-life. This was because growth from the viable micro-organisms that were present occurred to such an extent as to eliminate the differences between the DEFT and total viable counts (Copin and Bourgeois, 1992).

A 'BCR' (Commission of the European Communities, Community Bureau of Reference) collaborative study by eight laboratories, of 192 samples, including allspice, whole white pepper, whole and powdered black pepper, paprika powder, cut basil, cut marjoram and crushed cardamom, was reported by Wirtanen *et al.* (1993). Average values for the differences between DEFT and aerobic plate counts were 5.1 and 6.1 log units for 5 and 10 kGy irradiated samples, respectively. The differences for unirradiated *spices* were insignificant. The variability between laboratories was acceptable.

There may be problems of interpretation resulting from varying microbial floras, with different radiation sensitivities, existing in different batches of foods. In addition, problems can arise from processes other than irradiation that inactivate *bacteria* but leave them acridine orange fluorescent. However, for foods in which the normally expected flora is well known, deviations from the expected viability detected by this procedure can give valuable indications of whether radiation has been applied, and some indication of dose.

See also Detection.

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DNA damage

Since DNA is the key target molecule in many of the *applications* of food irradiation, it is logical that DNA damage should be a focus for attempts to derive methods to detect whether or not a food has been irradiated, and to quantify the dose received. *Ionizing radiation* affects DNA in a number of ways. It causes chemical changes in specific nucleotide bases; it causes single strand breaks, and it causes double strand breaks. These changes have formed the basis of proposed *detection* methods. For example, Pfeilsticker and Lucas (1988) showed that levels of thyminglycol, generated by reaction of radiolytically-derived *hydroxyl radicals* with bases in DNA, rose in a dose-dependent manner in irradiated *fish* and *poultry*.

Alkaline sucrose gradient centrifugation is a standard technique for detecting strand breaks. Retention of DNA on polycarbonate filters, following denaturation at high pH, has been proposed as a relatively straightforward way of quantifying the extent of damage, e.g. in irradiated lobster (Flegan and Copin, 1988). One of the products of irradiation of DNA, which may form the basis of a *detection* method, is dihydrothymidine. This is produced under oxygen-free conditions by the reaction of water-derived *free radicals* and thymidine in DNA (Deeble *et al.*, 1990; 1994). Microgel electrophoresis of DNA detects the change in mobility of DNA fragments produced by irradiation and may form the basis of methods that are reasonably specific for irradiated foods (Haine and Jones, 1994; Delincee, 1994; Bergaentzle *et al.*, 1994).

Further progress may result from the use of more specific DNA probe methods, in order to exclude the problem of the interfering non-irradiation-induced damage.

See also Detection; Comet assay.

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2-Dodecylcyclobutanone

A dose of 4.7 kGy generated sufficient 2-dodecylcyclobutanone from chicken for *detection* by solvent extraction and selected ion monitoring (Boyd *et al.*, 1991). The material was detectable for at least 20 days after irradiation, and was not found in unirradiated control samples. 2-Dodecylcyclobutanone has been proposed as another potential indicator of irradiation of *poultry* and other foods containing lipids (Stevenson *et al.*, 1990; McMurray *et al.*, 1994).

Coupling to an enzyme-linked immunosorbent assay (ELISA) test, using antibodies raised against cyclobutanone haptens, may further enhance the sensitivity and specificity of this technique (Hamilton *et al.*, 1994).

See also Detection.

References

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Dose

The absorbed dose of radiation is defined in terms of the energy absorbed by the substance irradiated. The SI unit of radiation dose is the *gray* (Gy), which is defined as 1 joule per kg. Doses used in food irradiation are usually quoted in kilograys (kGy). The *gray* replaces the older unit, the *rad*.

1 Gy = 100 rad
1 kGy = 100 krad
10 kGy = 1 Mrad (10^6 rad = 1 Mrad)

See also Dosimeter.

Dose distribution

The dose distribution in a food product is the variation in the absorbed dose throughout the product between the minimum (D_{min}) and the maximum (D_{max}) absorbed dose.

Dose uniformity is defined as the ratio of maximum absorbed dose (D_{max}) to minimum absorbed dose (D_{min}) in a product. The ratio D_{max}/D_{min} is termed the overdose ratio and should be kept to a minimum. Usually this value will not be more than 2.0, while a ratio of 1.5 is a more typical figure (ACINF, 1986). For example, if D_{max} = 12 kGy and D_{min} = 8 kGy, the overdose ratio = 1.5 and the overall average dose = 10 kGy.

The overall average dose received by a product is difficult to measure (Sharpe, 1990). It requires the distribution of a large number of *dosimeters* throughout the product. The overall average dose is approximately $(D_{max} + D_{min})/2$ but this estimate becomes increasingly inaccurate as the overdose ratio increases.

The concept of overdose ratio for *electron beam* irradiation is valid but the relationship between D_{max}, D_{min} and average dose is not straightforward (Sharpe, 1990).

It is necessary to achieve as uniform a dose as possible within a food product, in order to retain food quality, and meet legislative and *economic* requirements. Dose uniformity will depend on product thickness and density. Optimum homogeneity of bulk density is desirable (IAEA, 1992). Two-sided irradiation of a product improves dose uniformity (see Figures 5 and 7, page 56).

See also Dosimeter; Facilities.

References

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IAEA (1992) *Training Manual on Operation of Food Irradiation Facilities*, International Atomic Energy Agency, Vienna, ICGFI Document No. 14, pp.73–4.

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Dose rate

Dose rate is the increment in absorbed dose during a given time interval (units = *gray* per second).

Irradiation of food using a *cobalt-60* source involves irradiation at low dose rates in comparison to the high dose rate possible with *electron beam* machines. The dose rate from *electron accelerators* is usually between 10^4 and 5×10^8 Gy per second compared to below 10 Gy per second from a *gamma ray* source (Farkas, 1988).

In theory, at high dose rates typical of *electron accelerators*, *free radicals* are formed in such high concentrations that recombination, rather than reaction with other entities within the food product, is likely. In addition, at very high dose rates, the oxygen in the food system can be depleted faster than it can be replaced, by the diffusion of atmospheric oxygen into the product. Anoxic conditions induced in this way could reduce the lethality of radiation (Hayashi, 1991). There is evidence to suggest that the biological effects of *electron beams* on *micro-organisms* and *insects* are slightly less than the effects of *gamma rays*, depending on a number of parameters, including oxygen concentration and water content. The effect of dose rate on the chemical reactions in foods is much smaller than the observed biological effects.

In practice, dose rate has little significant effect on the outcome of irradiation.

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Dose uniformity *see* Dose distribution.

Dosimeter

Purpose of dosimeters

Radiation processing of foodstuffs requires measurement of doses in the range 0.01–10 kGy. Measurement of doses in excess of 10kGy is needed for radiation sterilized foods. Dosimeters are used to ensure that the pre-determined dose has been delivered to the product. They accompany the product, e.g. are attached to the package during irradiation, and are read on completion of the treatment

Dosimetry measurements are essential for process validation and quality assurance, which are the necessary requirements of a regulatory framework. In addition, dosimeters are needed to optimize irradiation plant performance and cost effectiveness, i.e. for the successful commercial application of food irradiation (Glover, 1992). Routine dosimetry measurements must be documented and traceable to national standards (Codex, 1984).

Dosimeters measure the amount of energy absorbed by the material being treated. The types of dosimeters that are used in the control of food irradiation have been reviewed (Miller and Chadwick, 1989; Sharpe, 1990).

National standards

Routine dosimetry measurements at a facility need to be referred to a national standard and ultimately to a primary measurement of absorbed dose (in water), in order to conform with regulatory requirements. There is a well-established measurement hierarchy for this. Ionization chambers or calorimeters are used as national standards. These instruments measure the absorbed dose to carbon or metal, then theoretically convert to the absorbed dose in water.

National standards laboratories hold the accurate primary measurement standards. For example:

- National Physical Laboratory (NPL), Teddington, TW11 OLW, UK.
- National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899, USA.
- Riso National Laboratory, DK 4000, Roskilde, Denmark.

Reference dosimeters

The regular use of reference dosimeters ensures the reliability of routine dosimetry. Reference dosimeters are chemical dosimetry systems whose responses to radiation and other factors, such as temperature and dose rate, are reproducible and well characterized (see Table 7). Chemical dosimetry systems, such as Fricke, potassium dichromate and ceric-cerous sulphate are known as absolute dosimeters. The radiation chemical response is characteristic of the particular solution composition; the accuracy is guaranteed to within a few per cent. Relative dosimeters, such as alanine and radiochromic dye films, such as Red 4034 Perspex, exhibit high precision but are calibrated against a higher standard in the chain.

Many national standards laboratories, and also the *International Atomic Energy Agency* (IAEA), offer a dosimetry service. Reference dosimeters are mailed to customers, who irradiate them, and return them to the standards laboratory for measurement and dose evaluation. Alanine is the transfer dosimeter selected for a service operated on behalf of the IAEA by a commercial organization (GSF) in Munich. The aim of the service is harmonization of dose measurements worldwide. In the UK, potassium dichromate, produced by NPL, is the reference dosimetry system.

Table 7 Reference dosimeters (after Sharpe, 1990).

Dosimeter	Reaction	Measurement	Dose range
Fricke	Oxidation of ferrous ion (Fe^{2+}) to ferric ion (Fe^{3+})	Concentration of Fe^{3+} measured spectrophotometrically	20–200 Gy
Ceric-cerous	Conversion of ceric ion (Ce^{4+}) to cerous ion (Ce^{3+})	Concentration of Ce^{4+} measured spectrophotometrically or by electrochemical potentiometric methods	500 Gy–50 kGy
Dichromate	Reduction of chromium Cr (VI) to Cr (III)	Decrease in Cr (VI) measured spectrophotometrically	2–50 kGy
Alanine-ESR	Free radical formation in alanine powder, pellets or thin film	ESR used to determine free radical concentration	10 Gy–100 kGy
Radiochromic dye films	Colour change in dye precursor molecules trapped in thin polymeric film	Colour change measured spectrophotometrically	1–100 kGy

Routine dosimeters

Routine dosimeters, in the form of dyed or undyed plastics, are used for the day-to-day monitoring of dose at an irradiation facility because of their ease of use and low cost. The plastic strips are preconditioned by the manufacturer and are sealed in foil satchets. The satchets are impermeable to oxygen and water transmission and protect the dosimeters against changing atmospheric conditions and surface scratches. In general, routine dosimeters are based on a chemical change that is linear within a practical dose range, e.g. a change in colour in radiation-sensitive dyes.

Dosimeters that are based on undyed plastics include polymethylmethacrylate (PMMA), Perspex and cellulose triacetate. Commercial systems such as Perspex HX and Radix are available. Radiation degradation of these polymers results in the generation of unsaturated molecules, which absorb in the UV region of the spectrum. Changes in optical absorbance are read in a UV spectrophotometer.

Dosimeters based on dyed plastics include dyed PMMA and radiochromic films, dyed polyamide, polyvinyl butyral and cellulose triacetate films. The reaction of the dye with the radiation species of the polymer matrix gives rise to a radiation-induced change in optical absorbance. This is determined at the appropriate wavelength by a spectrophotometer and is a measure of the absorbed dose.

The nominal dose ranges for radiochromic and PMMA dosimeters are shown in Table 8.

Use of dosimeters

Dose measurement in a radiation facility is described in Glover (1992), Miller and Chadwick (1989), and Sharpe (1990). The absorbed dose of an irradiated product is determined from routine dosimeters either placed within, or attached to the outside of, the package being irradiated.

Before use, each batch of routine dosimeters must be calibrated, using dosimeters irradiated at predetermined doses by an approved calibration laboratory. In this way, the absorbed doses used for food products are traceable to national standards.

Choice of suitable dosimeter will depend on the magnitude of the dose to be measured (see Table 8). Gammachrome YR has been developed for low doses, in the 0.1–3 kGy range, appropriate for the treatment of foods. Choice will also depend on radiation source. Although there is very little dose rate dependence with *gamma-* or *X-radiation*, there are known to be pronounced effects with *electron accelerators*.

Dosimetry standards

The American Society for Testing and Materials (ASTM), Philadelphia, PA, has published a number of guidelines related to dosimetry of irradiated food and the food irradiation process, including:

Table 8 Nominal dose ranges for routine dosimeters (after Glover, 1992).

Dosimeter	Dose range (kGy)
Radiochromic film dosimeters:	
Far West Technology FWT 60–00	1–50
GafChromic Dosimetry Media	0.05–30
Riso B3	1–200
PMMA dosimeters:	
Harwell Red 4034	5–50
Harwell Amber 3042	1–30
Harwell Gammachrome YR	0.1–3
Radix RN15	5–40
Red Gammex	5–50

- ASTM Standard E1204, Practice for Application of Dosimetry in the Operation of a Gamma Irradiation Facility for Food Irradiation Processing, Annual Book of ASTM Standards, Vol. 12.02 (1992).
- ASTM Standard E1261, Guide for Selection and Application of Dosimetry Systems for Radiation Processing of Food, Annual Book of ASTM Standards, Vol. 12.02 (1992).
- ASTM Standard E1431, Practice for Dosimetry in Electron and Bremsstrahlung Irradiation Facilities for Food Processing, Annual Book of ASTM Standards, Vol. 12.02 (1992).

See also Facilities.

References

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Dried egg *see* Egg – dried.

Dried fish *see* Fish – dried.

Dried foods

Dried foods, such as *cereal grains*, *legumes*, *cocoa beans*, *coffee beans*, *dried fruit*, *nuts* and *dried fish* are susceptible to *post-harvest losses* due to *insect* infestation (Anon, 1989). A dose of 1 kGy or below is adequate for disinfestation of all *insect* pests in dried food. To protect foodstuffs from *mould* spoilage, a dose of 3 kGy or more is required.

Spices, condiments, herbs, *herbal teas*, *dried vegetables* and other food ingredients can become a source of food contamination. Such dried ingredients are often heavily contaminated with *micro-organisms*. A dose of 5–10kGy is an effective decontamination treatment.

Dried foods are more resistant than fresh foods to the effects of ionizing radition because their low water content suppresses most of the indirect effects of radiation.

See also Direct and indirect action of ionizing radiation; Ionization; Water activity.

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Dried fruit

To control insect disinfestation, the recommended dose is less than 1 kGy.

Insect disinfestation

Insect disinfestation contributes to serious *post-harvest losses* of dried fruit in many countries. The use of irradiation as an alternative to the use of chemical fumigants, such as methyl bromide or phostoxin, is attractive. The use of insect-proof *packaging* is essential in order that reinfestation does not occur. The *insect* resistance of different *packaging* materials has been considered (Highland, 1991).

The radiation dose required for *insect* control depends upon the radiation sensitivity of the *insect* species and the stage of development. A dose of 0.4 kGy was sufficient to control Indian Meal moths, *Plodia interpunctella*, or saw-toothed grain beetles, *Oryzaephilus surinamensis*, in raisins, zante currants, prunes and dried *apricots* (Brower and Tilton, 1970). If only eggs or larvae were present, a dose of 0.2 kGy was sufficient. In dried *apricots* and *figs*, infested with *Corcyra cephalonica* and *Cadra cautella*, or dried *dates* and raisins, infested with *Tribolium castaneum*, a radiation dose of 0.25 kGy needed to be combined with storage at low temperatures (10–20°C) to check infestation for one year (Wahid *et al.*, 1989).

A radiation dose of 0.7 kGy was more effective than methyl bromide fumigation for the disinfestation of dried *dates* infested with *Ephestia cautella* and *Oryzaephilus surinamensis* (Ahmed *et al.*, 1985). For *dates*, infested with *Ephestia cautella*, a *combination treatment* of 0.7 kGy at 25°C, followed by exposure to heat (40°C for 48 h), was superior to radiation treatment alone (Ahmed *et al.*, 1986).

Product characteristics

In view of their low moisture content, dried fruits are less sensitive to radiation-induced changes in quality than fresh *fruit*. Radiation doses appropriate for disinfestation did not affect the *texture* or *flavour* of *dates* (Wahid *et al.*, 1987). Nutrients and *flavour* of dried *dates* were unchanged at doses of the order of 1 kGy (Thomas, 1988). Doses in excess of 4 kGy can modify the *texture* of dried fruit (Farkas, 1988). Swelling and cooking properties may be improved at the higher dose level.

Storage of dried fruit in coloured polyethylene may help protect *colour* and reduce *ascorbic acid* losses more than clear material during long-term storage (Wahid *et al.*, 1989).

Potential use

Legal clearance for radiation disinfestation of dried fruit is given in several countries (see Table 10, page 86). The *economic* benefits of irradiating dried fruit in Pakistan have been discussed (Khan, 1993).

See also Insect disinfestation; Legislation; Packaging.

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Dried vegetables *see* Vegetables - dried.

D-value

'D' refers to 'decimal' and is the radiation dose required to inactivate target cells by 90%, i.e. by one log, or to 1/10th of the original number. D-value (sometimes written D_{10}-value) should strictly only be used when inactivation kinetics are exponential ('log-linear'). The D-value then gives the slope of the inactivation curve when the log of the number of survivors is plotted against dose on a linear scale (see Figure 10, page 104).

When inactivation curves are not exponential, e.g. when, as commonly occurs, there is a shoulder before exponential inactivation commences, D_{37}-value is sometimes used, to give the dose needed to reduce initial numbers to 37% of the starting value. The value of the D_{37}-value in such instances is that it can be taken as the dose required to kill a single cell or viable unit (Moseley, 1989).

See also Micro-organisms – relative resistance; Tables 13, 14 and 18 (pages 104 and 131).

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E

***Echovirus** *see* Viruses.

Economics

Economic feasibility

The economics of food irradiation processing have been considered for a number of applications (Food Irradiation Newsletter, 1983; 1984; Morrison and Roberts, 1985; van Dijk and Tijdink, 1987; IAEA, 1993). It is recommended that detailed feasibility studies are carried out on individual products, in specific locations, for each application. Many factors and variables need to be considered, including raw material availability, market potential for the irradiated product, the technical feasibility of the treatment, legal aspects, and comparative figures for alternative technologies. Specific information, which is required for an economic analysis of a commercial application, is given in detail in Urbain (1993).

Estimating the cost of an irradiation facility

A major contributor to the total cost of an irradiation facility is the investment in the radiation source. The physical characteristics of the radiation source are important. *Gamma rays* and *X-rays* can penetrate pallet loads of foods; high-energy *electrons* of permitted energy levels (10 MeV or less) have limited penetration, and can treat foods with a thickness of up to approximately 8 cm. The investment in an *electron beam* or *gamma ray* irradiator, of equal capacity, is considered to be of the same order of magnitude (Leemhorst, 1993).

Radionuclide sources of *gamma-rays* must be periodically replaced since the intensity of the radiation gradually decreases as the *radionuclide* decays. The long-term cost of replacement needs to be evaluated. There are not the equivalent replacement costs for *electron accelerator* facilities, although there are high running costs, due to electricity consumption (Leemhorst, 1993). Operational costs for *radionuclide* and *electron beam* facilities are considered to be approximately equivalent.

Food irradiation plants have a high initial capital cost. Differences in the economies of size for *cobalt-60* and *electron accelerator* facilities have been demonstrated (Morrison, 1990). Economies of size exist if unit costs fall as the size of the plant increases. Capital and operating costs for an *electron accelerator* food irradiation facility (Defrise and Jongen, 1993) and for a *gamma irradiation* facility (Kunstadt and Steeves, 1993) have been identified.

A summary of factors that need to taken into account when estimating the costs of food irradiation include:

- Source costs – whether radionuclide or machine.
- Shielding, conveyors and other capital costs, e.g. ancillary building space and machinery.
- Operating costs, e.g. replenishment of cobalt-60 because of decay process; staff, maintenance and utility costs.
- Fixed and variable costs, investment, replacement costs.

In order to determine costs it is necessary to consider plant size or capacity. The factors affecting plant capacity are summarized as follows:

- amount of commodity,
- hours of operation (weekly/annual; processing schedules, e.g. seasonal products),
- product density and dimensions,
- dose and dose uniformity requirement,
- source efficiency, and
- handling considerations and transport.

Storage facilities, particularly low temperature (e.g. for irradiated *shrimps*, *meat* and *poultry*), and efficient transportation are considered to be vital. The costs of handling and transport can be significant. In addition, if irradiation is used in a *combination treatment* with other technologies, such as heat or vacuum packaging, costs will be even higher.

A summary of costs of a food irradiation facility is given by Urbain (1986):

- Operating costs are similar to those of any food processing facility (exception: *gamma radiation* source replenishment).
- Fixed costs are moderately high and require fairly high throughput for their support.
- Substantial investment, in the range of 1–3 million US dollars.

Other factors affecting economics

A food irradiation facility needs a very high throughput to be economic. This is an important issue for an integrated in-plant facility, in which irradiation treatment is one step of a food processing operation. Many *fruits*, *vegetables* and *fish* are seasonal commodities and may only be high volume for a relatively short time. A multipurpose contract service irradiator, to which a range of foods are transported for irradiation, may be advantageous for these types of products.

Costs of transportation and handling could be particularly high for a multipurpose irradiator. In addition, accommodating products of different density, dose and *packaging* requirements, possible problems of scheduling and handling different types of product, add to the cost of a multi-purpose irradiator. The use of contract service type irradiators and integrated in-plant irradiators are discussed by Urbain (1993).

In addition to technical and operational factors, legal costs, such as licensing and inspection, need to be taken into account. Consumer acceptability and marketing will be influenced by local circumstances and conditions.

Unit processing costs

In a study of the cost of a number of food irradiation applications, unit costs of 0.1–0.15 US dollars per kilogram were calculated (Morrison, 1990). It was concluded that irradiators must treat 23 million kg, or more, food per year, in order to capture production economies, and obtain a unit cost below 0.04 US dollars per kg. Such a constant high throughput could be provided by the chicken packing industry in the USA. The average cost per kg of irradiating food was similar for *electron accelerators* and *cobalt-60* irradiators.

In recent marketing trials in the USA, the costs of irradiating *strawberries*, *onions*, *oranges*, *grapefruit*, *tomatoes* and *mushrooms* were 0.04 US dollars per kg (Corrigan, 1993); 0.02 US dollars per lb was the cost of irradiating fresh *poultry* (Pszczola 1993). A cost of 0.165 US dollars per kg has been quoted for irradiating *spices* (Modak, 1993).

Cost-benefits of irradiation processing

Cost-benefits of irradiation processing for a food can be achieved by enlarging existing markets or expanding into new markets, e.g. increased shelf-life of fresh *meat* and *fish*, quarantine treatment of fresh *fruit* and *vegetables* (Urbain, 1993). In addition, elimination of health hazards present in certain foods, e.g. control of foodborne pathogenic *bacteria* in *chicken*, or food-borne *parasites* in *pork*, would provide public health benefits.

The costs and benefits of irradiating a range of foods in different countries have been evaluated (IAEA, 1993). There is evidence for cost effectiveness of irradiating *poultry* products, in order to provide consumer protection against salmonellosis and campylobacteriosis. In addition, the safety of *seafood*, Camembert cheese and red *meat* could be improved by irradiation treatment.

The economic feasibility of reducing *post-harvest losses* of food, caused by *insect* infestation, microbial spoilage or physiological changes, such as sprouting, has been considered (IAEA, 1993). There is evidence to suggest that quarantine treatment of fresh *fruits* and *vegetables* would be economically viable, in view of the planned restrictions on methyl bromide use. Irradiation quarantine treatment, for *fruits*, *cereal grains*, *dried fruits* and *cocoa beans*, could result in improvements in international food trade.

See also Facilities; Ionizing radiation.

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Eggplant *see* Aubergine.

Eggs – dried

For elimination of salmonellae, the recommended dose is 3 kGy or below.

Treatment

Dried egg products are used in the preparation of a variety of processed foods, including baked goods, soup, icecream, confectionery, and pet foods. Egg powder can be contaminated with *Salmonella* through *poultry*. Although numbers of the organisms are reduced by drying, there can still be a problem. There is only a small safety margin between the thermal process that provides a reduction in *Salmonella* and a heat dosage that damages the functional properties of dried egg (Farkas, 1988). Irradiation has been suggested as an alternative measure to heat treatment to pasteurize dried egg products.

Dose requirements for *Salmonella* inactivation in dried whole egg, egg yolk, and egg white were found to be in the range 3–6 kGy (Farkas, 1988). In dried egg powder, inoculated with *S. lille*, *S. enteritidis* and *S. typhimurium*, a reduction factor of 10^3 was accomplished with a dose of 2.4 kGy, and a reduction of 10^6 at 4.8 kGy (Matic *et al.*, 1990).

Product characteristics

Doses of the order of 5 kGy, which give significant reduction of *Salmonella* in egg products, result in the formation of *off-flavours*, and adverse affects on functional properties (Farkas, 1988; Diehl, 1983). At these dose levels, there is lower egg foam stability and viscosity; cake volume is lower in cakes made from irradiated eggs (Narviaz *et al.*, 1992). In addition, pigment loss and increased rancidity occur.

The organoleptic properties of whole egg powder, as well as scrambled egg and mayonnaise prepared from irradiated egg powder, deteriorated at doses above 3 kGy (Katušin-Ražem *et al.*, 1989). Doses of 3 kGy resulted in losses of the order of 20% for *retinol* and carotenoids. There were no losses of *thiamine* or *riboflavin* at this dose level. A radiation dose of 2 kGy is recommended as an effective dose for inactivating *Salmonella* and reducing the microbial load, while preserving the physicochemical properties of the product (Narviaz *et al.*, 1992).

Dried egg white is less sensitive to oxidation than whole egg and dried egg yolk (Diehl, 1983). Improvement in the functional stability of irradiated egg white powder using doses above 2 kGy has been reported (Clark *et al.*, 1992).

Enhancement of the formation of cholesterol oxidation products by *ionizing radiation*, even at 1 kGy, could limit the potential application of radiation treatment of egg powder (Lebovics *et al.*, 1992). Cholesterol oxidation products have undesirable health implications.

Potential application

Irradiation of egg products for microbial control is legal in France, Mexico and South Africa (see Table 10, page 86). Powdered egg has been treated to control salmonellae in the Netherlands (Table 5, page 32).

See also Eggs – fresh; Legislation; Retinol; Salmonella.

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Eggs – fresh

It is recognized that eggs can be potential sources of *Salmonella* food poisoning. Present methods of control, such as a chlorine dip, are effective against post-laying contamination. Irradiation has been suggested as a cold pasteurization process to control internal infection by the organism.

The use of irradiation to control *Salmonella in* fresh egg and egg products has been advocated by Harewood *et al.* (1993). Eggs treated with doses of 1.5 kGy, and stored at 4°C for 25 days, resulted in no significant difference in the sensory qualities of soft boiled eggs or scrambled eggs. There was a 73% retention of vitamin A. At 3.0 kGy, organoleptic changes were evident in the cooked products and vitamin A content was reduced to 20%.

There is evidence that irradiation adversely effects the internal quality of fresh eggs (Ma *et al.*, 1990). Doses between 1–3 kGy weakened egg shell and membrane, and caused fading of yolk *colour.* Off-odours and *flavours* were apparent. However, functional properties of egg white and egg yolk were not adversely affected, and whipping and emulsifying properties were substantially improved. Angel cakes prepared from irradiated egg white had lower batter density and a higher cake volume. This suggests that there may be potential for irradiation to enhance the functional properties of egg products.

Complete inactivation of *Salmonella* cells in liquid whole egg using thermoradiation has been demonstrated. A combination of a heat treatment of 63°C and a dose of 0.37 kGy, at pH 5.5, was effective in improving the hygienic quality of liquid egg (Schaffner *et al.*, 1989).

See also Eggs – dried; Salmonella.

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Electromagnetic spectrum

The electromagnetic spectrum is shown in Figure 1.

See also Ionization; Ionizing radiation.

Electron

An electron is a negatively charged particle that is an integral part of every neutral atom. Free electrons can be produced, collected into beams, and accelerated to a high energy level in electrical machines, known as electron accelerators or electron beam machines.

See also Facilities; Ionizing radiation.

Electron accelerator *see* Facilities.

Electron beam machines *see* Facilities.

Electron spin resonance (ESR)

Electron spin resonance is one of the most promising of the physical techniques for the *detection* of irradiated

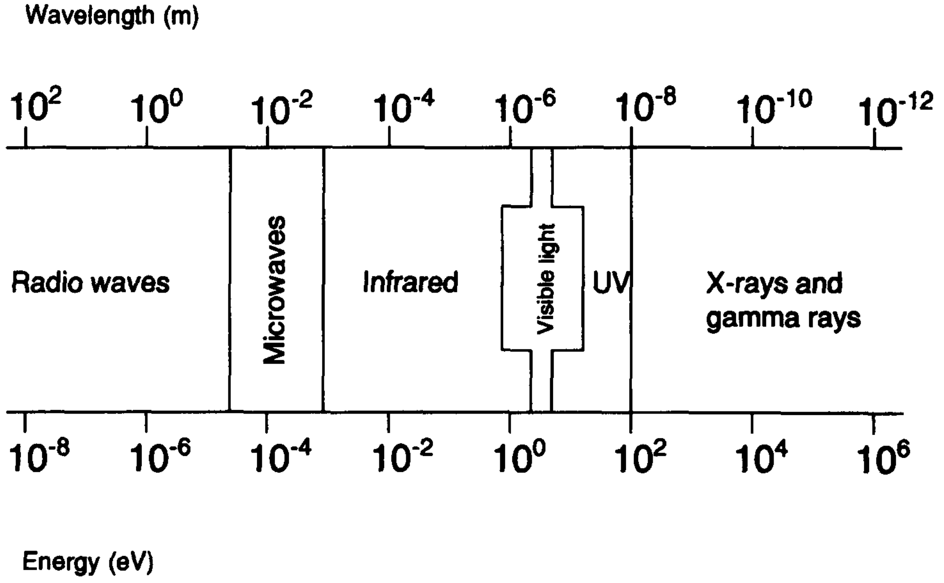

Figure 1 Electromagnetic spectrum. Simplified form of the spectrum showing wavelengths and photon energies corresponding to the approximate boundaries between the various bands (not drawn to scale).

foods. It relies on the *detection* of trapped *free radicals* and, therefore, is satisfactory only for foods in which radicals are essentially immobilized, such as *dried foods*. However, in some such foods (e.g. certain *spices*), fading of the signal leads to loss of effectiveness in long stored products (Yang *et al.*, 1987). However, most importantly, sufficient immobilization occurs in bone, so the technique has been successful in the identification of irradiation of *poultry, fish, frog legs* and crustacea with hard cuticles (Desrosiers and Simic, 1988; Dodd *et al.*, 1988; Stewart and Stevenson, 1994).

A major study of the effects of dose (2.5 to 10 kGy), storage time (0 to 28 days) and temperature (-20 and +5°C) on the ESR signal from bone in chicken leg 'drumsticks' was undertaken by Stevenson and Gray (1989). Data were obtained quantifying how ESR signal strength increased with dose, and then decreased with subsequent storage, and more rapidly at 5°C than at -20°C. The results confirmed the view that ESR is a valuable method for the *detection* of irradiated *poultry* but also indicated that more research is needed to take account of the age of the bird, feeding regime, *packaging*, and post-irradiation processing, which can all influence the magnitude of the signal. Irradiated Norway lobster ('scampi') was correctly identified using the ESR signal induced in the cuticle (Stewart *et al.*, 1992). Desrosiers *et al.* (1990) reported the results of a multinational trial of ESR methodology targeting chicken bones, *frog legs* and *pork* ribs. Non-irradiated bones were all correctly identified and good estimates of absorbed dose were obtained.

A further EC Community Bureau of Reference co-trial, involving 21 laboratories (Raffi *et al.*, 1992), confirmed the quantitative value of ESR for chicken bones irradiated at 1–3 kGy and 7–10 kGy, although there was partial overlap between these close ranges. Similar studies with *beef* and trout bones, sardine scales, dried *grapes* and *papaya*, confirmed that they had been irradiated, but with poor indication of dose.

In *spices*, a central line of unknown origin was present in the ESR spectra of both irradiated and non-irradiated samples and interfered with *detection*. This was overcome by changing the measurement conditions (to low microwave power). Helle *et al.* (1992) detected two additional lines on both sides of the major signal. This line pair appeared only in the spectra of irradiated *spices*. A similar line pair was found in the spectra of irradiated nutshells and may derive from cellulose radicals. For some *spices*, especially paprika, the identification of irradiated samples by *detection* of the additional lines was possible even after long periods of storage.

The stones and seeds of *fruits* are suitable targets for ESR metholology so that, for example, ESR has been used to detect irradiation of *strawberries* by *detection* of the signals from achene 'pips' (Raffi *et al.*, 1988). A study targeting *poultry* bones, carp bones and scales, seeds of certain *fruits*, dehydrated mushrooms, *spices* and herbs (Stachowicz *et al.*, 1992) also confirmed the value of ESR, but highlighted the substantial variation in its sensitivity when applied to different foodstuffs.

See also Detection.

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Electron volt

The energy of the constituent particles, or photons, of ionizing radiation is measured in electron volts (eV). An electron volt is defined as the amount of energy gained by an *electron* when accelerated by a potential of one volt. The energy level of *electrons*, or *X-rays*, from electrical machine sources, and gamma-rays from radioactive sources are expressed as:

kilovolts (keV) = 1000 eV
mega-electron volt (MeV) = 1 million eV.

Endive (*Cichorium endivia*)
Doses in the range 0.25–2 kGy caused spotting and browning of endive, with no significant effect on decay (Bramlage and Lipton, 1965). A dose of 1 kGy increased the shelf-life of cut, prepacked endive, without excessive loss of *vitamins* or discolouration (Langerak, 1978).

References

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Langerak, D.Is. (1978) The influence of packaging on the quality of prepacked vegetables, *Annal de Nutrition et d'Alimentation*, **32**(2/3), 569–86.

Enterobacteriaceae *see* Escherichia coli; Salmonella; Shigella.

Enterococcus *see* Lactobacillus.

Enzymes
Enzymes have been increasingly employed to catalyze reactions on a commercial scale, e.g. for biotechnological purposes to produce pharmaceutical products, and also to produce or modify *food components* (e.g. glucoamylase; alpha amylase). Irradiation has been promoted as an efficacious decontamination technique that, at doses of 10 kGy or so, has little effect on enzyme activity (Wetzel *et al.*, 1985).

Immobilization media and supports for enzymes vary greatly in radiation sensitivity. For example, viscose acetate-catalase membranes became very brittle after irradiation, whereas nylon mesh was relatively unaffected even after a dose of 24 kGy (Abdul-Hamid *et al.*, 1991).

See also Proteins.

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Escherichia coli

General
Although most strains of *Escherichia coli* are harmless inhabitants of the gastrointestinal tracts of humans and other warm-blooded animals, a few strains are pathogenic. *E. coli* isolates are Gram-negative rods that are motile (though non-motile strains are known) and ferment lactose (though late lactose fermenters are known).

Four different groups of *E. coli* have been associated with human food-borne disease. These are the enteropathogenic ('EPEC') strains, the enteroinvasive ('EIEC') strains, the enterotoxigenic ('ETEC') strains and the enterohaemorrhagic strains ('EHEC'). The latter is the most important, with the particular serotype *E. coli* 0157:H7 being of most concern because of the seriousness of the diseases that it may cause. The three major syndromes associated with it include: haemorrhagic colitis; haemolytic uremic syndrome, which is a major cause of kidney failure in children and also affects old people; and thrombotic thrombocytopenic purpurea which, though rare, includes brain damage and results in a very high mortality.

Food-related outbreaks have been linked particularly to the ingestion of undercooked minced beef and raw *milk*. The organism occurs in *meats* other than beef as well.

Radiation resistance
Patterson (1988) reported *D-values* of about 0.3 kGy for *E. coli* irradiated in *poultry* meat. Irradiated at chill temperatures in beef, the *D-value* of *E. coli* O157:H7 was reported by Thayer and Boyd (1993) to be about 0.16 kGy. The effect of freezing on the resistance of *E. coli* irradiated in broth is shown in Figure 14, page 151 (Goldblith, 1971).

See also Meat.

References

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Patterson, M.F. (1988) Sensitivity of bacteria to irradiation on poultry meat under various atmospheres, *Letters in Applied Microbiology*, **7**, 55–8.

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Equilibrium relative humidity *see* Water activity.

Equipment *see* Facilities.

ESR *see* Electron spin resonance.

F

Facilities

General

There is wide expertise in the design, building and operation of both *radionuclide* and electrical machine irradiation facilities (Leemhorst and Miller, 1990). *Radionuclide* facilities are currently in use for the treatment of food, and for non-food applications, such as sterilization of medical supplies, and pharmaceutical, cosmetic and veterinary products. Electron accelerators are used in the manufacture of certain *packaging* materials (e.g. cling film) and in the treatment of plastic wire insulation to improve its properties. Commercial irradiation facilities for food are available in several countries (see Table 5, page 32).

Irradiation facilities could be operated as integral parts of food processing lines or as multipurpose service facilities on a fee basis (Urbain, 1993). Some form of refrigerated storage is necessary for certain foods. Food irradiation plants may be operated in batch or continuous mode. Batch facilities are considered to be more flexible and able to accommodate a wide range of doses (WHO, 1988). Continuous facilities are better able to accommodate large volumes of food product, especially when treating a single food at a specific dose.

Mobile irradiators have been used in research for the treatment of seasonal food, such as *fruits* and *vegetables*, and for *fish* irradiation on board ship.

Radionuclide and machine facilities

The international standard of irradiated foods (Codex, 1984) permits three types of *ionizing radiation* to be used: *gamma rays* from *radionuclides*, cobalt-60 or caesium-137; *X-rays* with energies of 5 MeV or less; and *electrons* with energies of 10 MeV or less. These restrictions ensure that the natural level of *radioactivity* in food is not increased.

Choice of facility depends on a number of technical and social factors and also on *economics* (see Table 9). An important technical factor relates to penetration of the type of radiation. *Gamma rays* and *X-rays* can penetrate pallet loads of food; in contrast, 10 MeV *electrons* can be used to perform one-sided irradiation of 4 cm targets (water equivalent) (IAEA, 1982). The limited penetration of electron beams restricts their use to treating the surface of foods, thin packages of food, shallow streams of grains, powders or liquids.

A food irradiation facility comprises:

- a source of radiation, i.e. *radionuclide* or electron beam;
- biological shielding to protect personnel operating the facility from radiation exposure;

Table 9 A comparison of radionuclide irradiators and electron accelerators (from Fink and Rehmann, 1994).

Radionuclide irradiator	**Electron accelerator**
Good penetration power of gamma rays – can be used to treat food in large packaging units	Relatively limited penetration power (5–8 cm)
Low dose rate	High, variable dose rate – allows high throughput, e.g. grain
High reliability	More sensitive to breakdown – need for specialized personnel for regular maintenance
Need to replenish radionuclide source	High requirements for power and cooling
	Machine can be switched off
	Small units of equipment could be integrated into a production line

- a carrier or conveyor system to bring the food product near to the source for processing;
- safety interlock/control console system. This ensures that conveyor movement occurs when the source is exposed or the machine switched on (no conveyor movement when source is 'safe' position or machine turned off) (Farkas, 1988).

A training manual on the operation of food irradiation facilities is available (ICGFI, 1992).

Radionuclide source irradiators

The *radionuclide* source commonly used to treat food is cobalt-60. Sources are encapsulated in stainless steel tubes to prevent any leakage during use in the radiation plant. The tubes are assembled into a suitable configuration, such as a rectangular or cylindrical frame; the arrangement is designed for maximum efficiency, so that there is a maximum ratio of energy absorbed in the product to energy emitted from the source.

The strength of the radiation source is expressed as *becquerels* or *curies*. A commercial food irradiation facility may have typically 37 petabecquerels (1 million curies) of cobalt-60, depending on application. The intensity of the radiation gradually decreases as the *radionuclide* decays, dependent on *half-life*. Cobalt-60 has a *half-life* of 5.3 years. In order to maintain a constant throughput capacity in an irradiation plant, an addition of about 12% of the original source activity of ^{60}Co per year is needed. Cobalt-60 is used in preference to caesium-137 because it is more readily available and convenient to use (ACINF, 1986).

Shielding in the form of thick concrete walls is provided to house the source. The walls of the irradiation chamber and the maze, through which access is made to the source, are constructed from concrete about 1.5 m thick. In addition, a deep pool of water (approximately 7 m deep) is used for storage of the source when it is not in use, and for manipulation during source replenishment. This prevents worker, and environmental, radiation exposure.

Gamma irradiation facilities differ in their conveyor systems. Product transport systems fall into four categories: tote box, carrier, pallet carrier and pallet conveyor systems (Farkas, 1988; Kunstadt and Steeves, 1993). A pallet-type cobalt-60 irradiator is shown in Figure 2. Containers of food are transported past the source on the transport system. The food receives an appropriate radiation dose depending on source strength and geometry, siting of conveyor, conveyor speed, and density and thickness of the product. Containers are conveyed through the facility in such a way as to achieve as uniform a dose as possible throughout the product.

Auxiliary systems are used, including equipment to deionize the water in the pool and remove excess heat, and air handling systems to vent the ozone produced from the irradiation of oxygen in the air (Farkas, 1988).

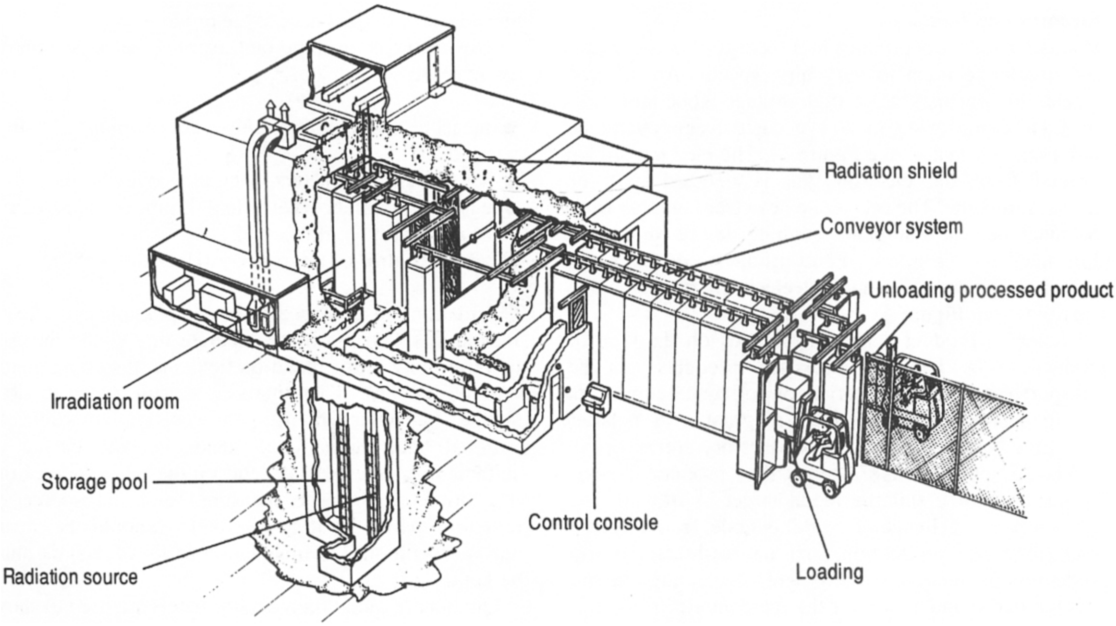

Figure 2 Pallet-type cobalt-60 irradiation facility (courtesy of Nordian International Inc., Canada).

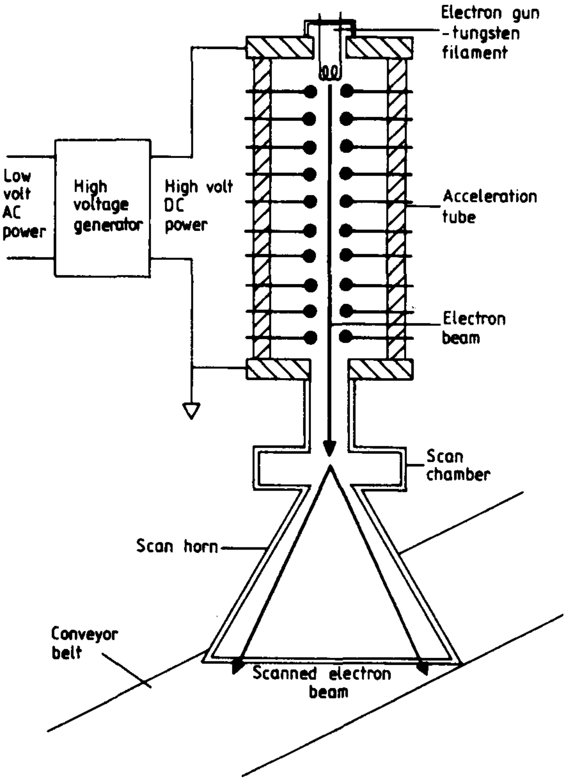

Figure 3 Simplified construction of an electron beam machine (courtesy of Leatherhead Food RA, UK).

Electron accelerators

Machine irradiators produce high-energy electron beams and accelerate them to very high speeds. An electron accelerator consists of a high-voltage generator connected to an electron gun, an evacuated acceleration tube and a beam scanner (see Figure 3). The electron stream emitted from the electron gun is injected into the accelerating tube. The accelerated electrons emerge from the machine, via a suitable scanning device, through a thin metal foil 'window'. Food products are treated as they pass through a curtain of electrons on a suitable conveyor (see Figure 4).

Choice of product conveyor depends on the type of product to be handled. Packaged products can be transported on monorail carriers or horizontal conveyors or cart systems. Food products in granule or powder form may be handled on belt or vibratory conveyors.

When *electrons* strike a target they produce *X-rays*. By insertion of a suitable metal target in front of the electron beam, a change of machine mode, from electron beam to *X-ray* production, can be facilitated. *X-ray* production is relatively inefficient, depending on the target material and energy of the incident electrons, e.g. at 10 MeV, conversion efficiency is typically 18%. Problems of power output may be solved with new technology (Takehisa *et al.*, 1993), with the possibility of using both *electrons* or *X-rays* at the same facility (Defrise and Jongen, 1993).

Biological shielding to prevent personnel exposure, in the form of thick concrete walls, and ventilation of the irradiation cell are required, as in *radionuclide* facilities (Farkas, 1988).

An electrical machine source can be switched off when not in use, and when personnel need to enter the cell to load the product or to carry out servicing and maintenance. For this reason, electron accelerators could be more easily incorporated into a processing or packaging plant, than a *radionuclide* source.

Process control

Process control at an irradiation facility is vital. This is because there are no simple tests that distinguish irradiated from unirradiated products or quantify dose. Adequate documentation must accompany all consignments of irradiated food, in order to distinguish the foods that have been irradiated and to provide information on treatment dose.

Control of food irradiation in all types of facilities involves monitoring physical parameters and measuring absorbed radiation dose (Codex, 1984). Detailed information on plant operation and process control is given in ICGFI (1992).

Parameters involved in the control of radiation dose, from a *radionuclide* source, are source size and geometry, the conveyor speed or time the package is exposed to the source, and the density and thickness of the product. For an electron beam machine, the radiation dose will depend on machine parameters – voltage and beam current – and speed of the conveyor belt. In addition, dose depends on the density and thickness of the product.

Dosimetry is an important aspect of process control. Its purpose is to:

- measure the radiation *dose distribution* in a food product
- set process parameters, such as conveyor speed
- ensure compliance with dose limits for a particular food (quality control), and
- verify control of the process (Pothisiri, 1989).

Calculations of absorbed dose are possible but experimental dosimetry is more accurate due to the intrinsic heterogeneity of the radiation field and absorbing matter (ACINF, 1986). Quantitative measurement of dose should be achieved using *dosimeters* traceable to national and international standards. The choice of suitable *dosimeter* will depend on the magnitude of the irradiation dose to be measured and the source of radiation used. Routine dosimetry should be made during operation. Documentation of these records must be kept.

Qualitative radiation indicator labels are used to show whether a product has been irradiated. These are useful to ensure separation of treated and untreated products.

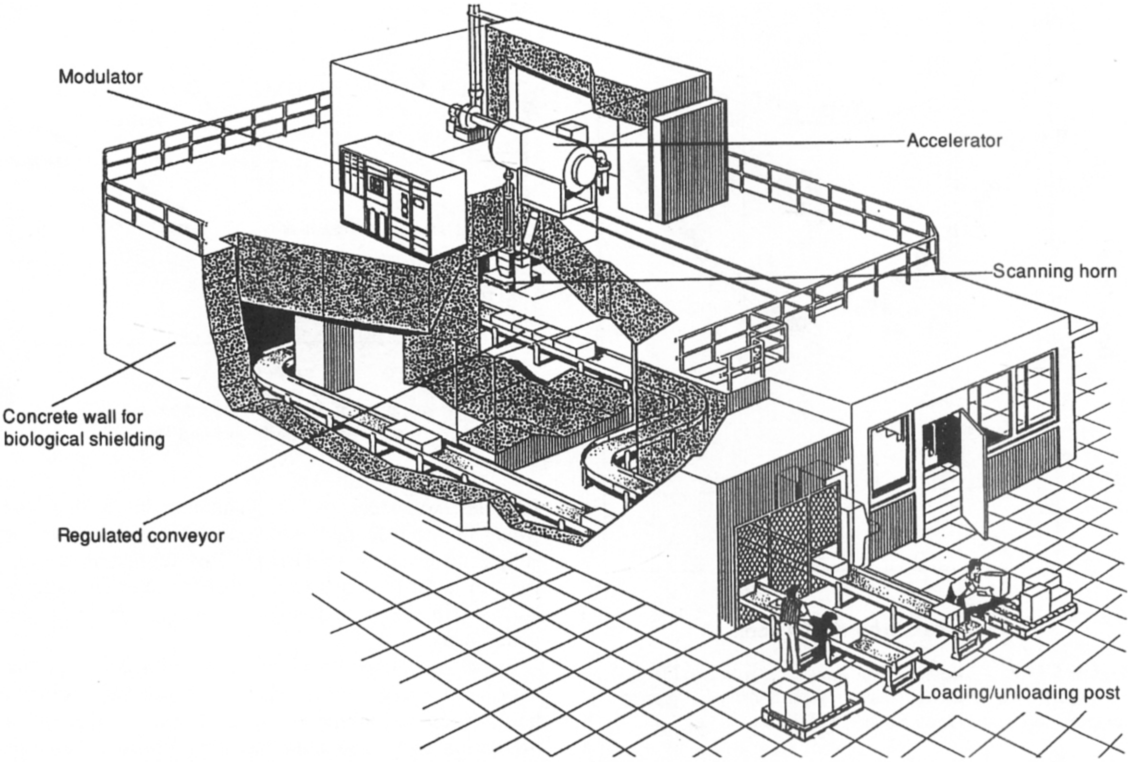

Figure 4 Commercial electron beam machine facility (courtesy of MeV industrie SA, France).

Radiation dose distribution

The *dose distribution* throughout the food should be determined by suitable numbers of *dosimeters* randomly distributed throughout the volume of the product. The arithmetic mean of all the *dosimeter* readings is designated the 'overall average dose'. Minimum (D_{min}) and maximum dose (D_{max}) positions can be established. These measurements are necessary for each new food product or for any alteration in product characteristics, and if there are changes in source geometry or conveyor system.

Non-uniformity of dose is unavoidable to a certain extent because of the fundamental properties of radiation and the detailed geometry of the source and the variability of shape, density and composition of the products (ACINF, 1986). The degree of non-uniformity of dose within a food sample may be expressed as the ratio between D_{max} and D_{min}. The ratio of D_{max} to D_{min} is termed the overdose ratio and should be kept to a minimum. The overall average dose is $(D_{max} + D_{min})/2$.

Gamma rays and X-rays: Penetration of these forms of radiation depends on their energy, and the density and thickness of the product. In general, this type of radiation is most useful for treating pre-packaged, bulky items. *Gamma rays* and *X-rays* are attenuated exponentially by absorbing material (IAEA, 1982). The resulting dose–depth distribution of food products closely resembles an exponential curve (see Figure 5). Products are normally irradiated from both sides so that the food receives as uniform a dose as possible throughout the package.

High-energy electrons: Penetration of high-energy electrons in a food product is limited and is closely related to its energy (see Figure 6). Penetration also depends on the density of the product. Penetration by 10 MeV electrons is limited to 3.9 cm thick targets (density 1), with dose uniformity approaching 1.3 (IAEA, 1982). Two-sided irradiation can be used to increase penetration, so that 10 MeV electrons can be used to treat food approximately 8 cm thick (density 1) with a dose uniformity of 1.3 (see Figure 7). Thus, irradiation by high-energy electrons is suited to thin targets of food moving through the electron beam, such as grain or thin packages of food. The limitations of product thickness in electron mode could be overcome if the machine could be used in *X-ray* mode.

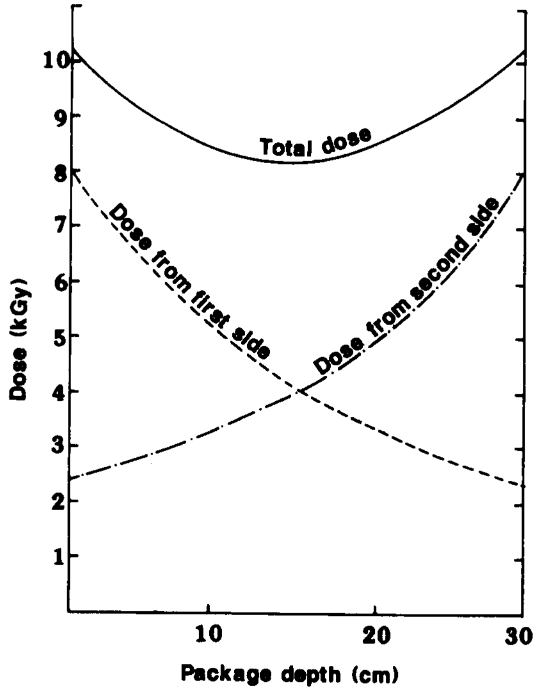

Figure 5 Depth–dose curves in a package irradiated from both sides by a cobalt-60 source (target density 0.3 g/cm^3) (courtesy of Leatherhead Food RA, UK).

Licensing and inspection

Facilities need to be licensed, registered and controlled by appropriate national authorities (Codex, 1984). Licensing requirements will vary from country to country. Strict control measures for food irradiation facilities are necessary to guarantee the quality and *safety* of food. In addition, food irradiation plants are subject to inspection and control by regulatory authorities, in order to make certain that the relevant national and international radiological *safety* standards are maintained.

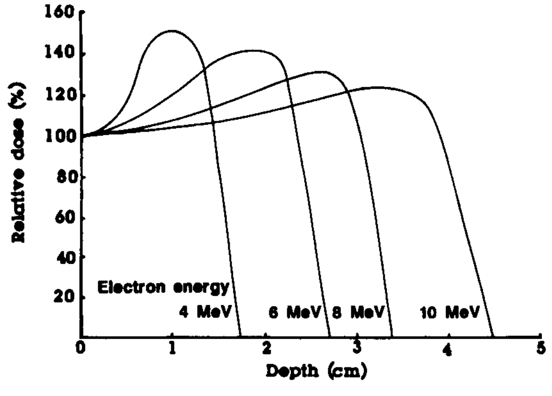

Figure 6 Penetration of electrons of different energies in water (courtesy of Leatherhead Food RA, UK). The shape of the rising curve is due to secondary electron formation. Secondary electrons, which have lower energy, are absorbed preferentially.

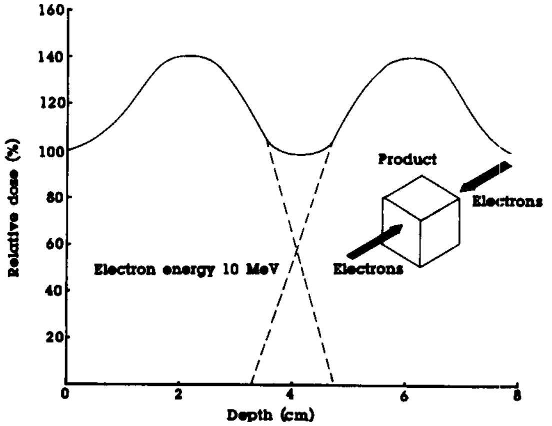

Figure 7 Penetration of 10 MeV electrons using two-sided irradiation (courtesy of Leatherhead Food RA, UK).

Inspection of food irradiation facilities is carried out in order to verify that the facility is operated according to the licence requirements, and to ensure that good irradiation and good manufacturing practices are followed (ICGFI, 1992). To facilitate inspection, records must be kept of all operations. Records for each food consignment should include the date of treatment, the type of food or ingredient treated, a batch identifier and details of overall average dose received. Details of the dose should include parameters used, together with records of *dosimeter* readings. Such documentation needs to accompany the food throughout the full processing chain and be available to inspection by regulatory authorities (ACINF, 1986).

The following documents are available from the *International Atomic Energy Agency*:

- Guidelines for Preparing Regulations for the Control of Food Irradiation Facilities, ICGFI Document No. 1, Vienna (1991).
- An International Inventory of Authorized Food Irradiation Facilities, ICGFI Document No. 2, Vienna (1993).

See also Codes of practice; Control of food irradiation; Dose distribution; Dosimeter, Economics; Ionizing radiation; Radionuclide; Safety.

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FAO/IAEA/WHO

The Food and Agriculture Organization (FAO) of the United Nations, the *International Atomic Energy Agency* (IAEA) and the World Health Organization (WHO) collaborate on numerous areas of research relating to food irradiation. Reports of a Joint FAO/IAEA/WHO Expert Committee on Food Irradiation (JECFI) have been central to the international acceptance and progress of food irradiation.

See also History.

Fats *see* Lipids; Volatiles.

Fatty acids *see* Lipids.

Fatty foods

Auto-oxidation of fats is promoted by irradiation. It is recommended that the irradiation, and post-irradiation storage, of foods containing *lipids* as major components should be carried out in the absence of *oxygen* (Urbain, 1986). In this way, off-flavours and off-odours associated with the irradiation of high-fat foods are minimized.

See also Flavour; Dairy products; Fish; Meat.

References

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Feeds *see* Animal diets.

Figs

The shelf-life of fresh figs is limited by fungal spoilage. Radiation doses of 2–4 kGy reduced surface *mould* in figs (Bramlage and Couey, 1965). Radiation injury in the form of a dark brown surface *colour*, and drying of the *fruits* in storage, appeared to be variety dependent.

A *combination treatment* of a hot water dip (50°C, 5 minutes), followed by a dose of 1.5 kGy, is reported to be an effective treatment for figs (Padwal-Desai *et al.*, 1973). An extension of shelf-life of 3–4 days at room temperature, or 8–10 days at 15°C, was achieved. No appreciable changes in *flavour* or *texture* were observed.

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Figs – dried *see* Dried fruit.

Fish

For inactivation of parasites, and for a reduction in microbial load leading to an extension of refrigerated shelf-life and a reduction in pathogenic organisms, the recommended dose is 0.5–2.2 kGy.

Parasite control
Fish-borne, snail-borne and crustacean-borne parasitic diseases are found worldwide, with a high prevalence in Asia and Japan. This is due to consumption of raw or undercooked or fermented fish, which may contain parasitic cysts. Irradiation could be an effective control measure (IAEA, 1993).

Low radiation doses, below 1 kGy, are adequate to control liver flukes, such as *Opisthorchis viverrini* and *O. felineus*, and the Chinese liver fluke *Clonorchis sinensis* (see Table 17, page 121). At this dose level, the sensory quality of tilapia and silver carp, which are typical of fish that may be consumed raw as sashimi, was preserved (Liu *et al.*, 1991).

Parasites, such as *Gnathostoma spinigerum* and *Anisakis* spp. are more resistant to radiation (see Table 17). An effective dose, in excess of 2 kGy, is likely to have deleterious effect on the quality of fish.

Reduction in microbial load
Irradiation of fish could extend the storage life at refrigeration temperatures of fish fillets and steaks. Extension of refrigerated storage life would allow shipment, sale and consumption of fresh fish in areas that are remote from the sea or rivers.

In general, the pre-irradiation spoilage microflora of fish includes radiosensitive Gram-negative species such as *Pseudomonas* and *Flavobacterium*. Irradiation causes a change in microflora to predominantly Achromobacter (*Moraxella/Acinetobacter*) and/or Gram-positive elements such as *Micrococcus* or *Corynebacterium* spp. (Ingram, 1975). The pattern is affected by dose, pre-processing conditions, storage temperature and time, and *packaging*.

Fish and shellfish can be contaminated with pathogenic non-spore forming *bacteria* and *viruses*. The contamination may be due to polluted water or handling after the catch. Enterococci, *Vibrio* species and *Staphylococcus aureus* are significant causes of food poisoning. There is a high incidence of reported cases in Japan where the fish is consumed raw (Gilles *et al.*, 1989). Irradiation could effectively reduce levels of pathogenic organisms.

The risk of *Clostridium botulinum toxin* in fish treated with 1 and 2 kGy has been investigated (Eklund, 1982). In haddock and sole fillets, inoculated with *C. botulinum* spores, the margin of safety decreased as the dose increased. Spoilage preceded toxicity when 1 kGy treated fillets were stored at 3.3°C. At 2 kGy, treated fillets stored at 5.6°C became toxic more quickly, although time to spoilage increased. To ensure irradiated fish will spoil before *C. botulinum toxin* can develop, doses need to be limited to between 1–2 kGy and the temperature kept below 3.3°C.

Guidelines
A Code of Good Irradiation Practice for the Control of Microflora in Fish, Frog Legs and Shrimps is published by the International Atomic Energy Agency (ICGFI Document No. 10, 1991).

Treatment
Best results for irradiated fish are obtained if:

- cut portions are obtained from very fresh fish (if spoilage has occurred the treatment will not improve product quality);
- temperature after packaging and irradiation are as near to freezing point as possible (Nickerson *et al.*, 1983).

There is evidence that eviscerated but otherwise uncut or whole fish could be treated with *ionizing radiation* at 0.5–1 kGy on board ship to provide a better quality, and longer storage life, of the iced product.

Product characteristics
The effect of irradiation on a wide range of freshwater and marine fish has been comprehensively reviewed by Nickerson *et al.* (1983). More recent reports on fish include hake (Kairiyama *et al.*, 1990; Lescano *et al.*, 1990), cod (Thibault and Charbonneau, 1991a, b) and tilapia (*Oreochromis mossambicus*) and silver carp (*Hypophthalmichthys molitrix*) (Liu *et al.*, 1991). Optimal dose levels for both freshwater and marine fish are between 1–2.5 kGy for different species. This results in a 2–3 fold extension of shelf-life.

Fish and shellfish are rather more sensitive to radiation-induced organoleptic changes than *meats*. Volatile compounds identified in irradiated fish and shellfish are reviewed by Diehl (1983). At optimal dose levels, there may be a slight loss of the typical *flavour* of irradiated fresh fish. Off-odours may be detected, especially soon after treatment. Even at 1 kGy, some gourmets could detect off-odours and *flavours* (Houwing *et al.*, 1978). Fillets or steaks from white-fleshed fish give better results than those from dark-fleshed fish, which may develop rancidity. Deep-fat frying of irradiated fish may conceal slight irradiation *off-flavours*, which may be apparent in the steamed product. In general, the *texture* and appearance of irradiated fish are not affected. However, in salmon and trout, irradiation caused bleaching of the carotenoid pigments (Urbain, 1986). The *colour* of irradiated carp flesh appeared to be more reddish (Liu *et al.*, 1991).

Packaging
Use of appropriate *packaging* materials is essential to preserve the quality of irradiated fish. It has been recommended that low-fat fish such as cod, haddock or pollock should be pre-packaged in an oxygen impermeable container that prevents moisture loss and diffusion of *oxygen*. Fish fillets or steaks from fish higher in fat, such as English sole, halibut or petrale sole, benefit from pre-packaging under vacuum, to prevent the products becoming rancid during refrigerated storage (Nickerson *et al.*, 1983).

Fish products

The potential of *ionizing radiation* to reduce bacterial numbers in fish products has been studied. An increase in shelf-life was obtained in frozen minced cod (Da Ponte *et al.*, 1986) and red hake mince (Dymsza *et al.*, 1990), with low radiation doses. Irradiation of kamaboko, a Japanese fish-paste product, at a dose of 3 kGy, extended the product shelf-life approximately two-fold (Takehis and Ito, 1986).

Radiation (5–10 kGy) was an effective treatment for decontamination and pasteurization of *dried fish* powders with minimal effects on physicochemical properties and sensory quality (Cho *et al.*, 1992). Similarly, defatted fish protein concentrate, which is used in pet foods, was decontaminated with a dose of 5 kGy (Tsuji, 1983).

Combination treatment

A *combination treatment* involving a potassium sorbate treatment (5% solution, 40 seconds), prior to aerobic *packaging*, and a maximum dose of 1 kGy, has been recommended for cod fillets (Licciardello *et al.*, 1984). The treatment extended the period of acceptability, during iced storage, 2–3 times that of the untreated fish. Potassium sorbate may provide a safety factor for *C. botulinum toxin* production.

Pretreatment with a solution of sodium tripolyphosphate, prior to *packaging* and irradiation, has been used to prevent 'drip' or loss of fluids during fish storage. A combination treatment of 1.5 kGy with 10% sodium polyphosphate has been recommended for mackerel (Hussain *et al.*, 1985). An increase in shelf-life of up to 2 weeks, at 1–3°C, was obtained with minimal drip loss.

The shelf-life of fish may be increased by using a combination of irradiation and modified atmosphere packaging. A 60% CO_2 packaging atmosphere, in combination with a dose of 1 kGy, was shown to be advantageous for cod (Licciardello *et al.*, 1984). However, there was no advantage of a combination of modified atmosphere packaging (80:20 CO_2/air; 100% CO_2) with irradiation treatment (0.5–1 kGy) for catfish fillets (0–2°C) (Przybylski *et al.*, 1989). Irradiation alone at 1 kGy increased the shelf-life four-fold.

Dried cuttle fish is a valuable *seafood* in Vietnam. Microbiological levels can be reduced and food pathogens eliminated using a radiation treatment of 2–3 kGy alone, or in combination with benzoic acid or potassium sorbate (Yen, 1992).

Nutrition

Irradiation of fish up to 2.2 kGy, as recommended by the Joint FAO/IAEA/WHO Expert Committee (1981), does not cause significant changes in the nutritional quality of fish. *Protein* content or amino acid composition are unaffected with doses at this level. Losses of B-vitamins in fish may occur. The radiation sensitivity of *thiamine* in cod has been highlighted (Kennedy and Ley, 1971). The *thiamine* content of silver carp was reduced by 34%, after irradiation at 1 kGy, but *riboflavin* was unaffected (Liu *et al.*, 1991).

Detection

An effective method of detecting irradiated fish is ESR *detection* of bones, scales and shells.

Potential application

The effectiveness of irradiation as a method for increasing the shelf-life of fresh fish was demonstrated in the 1960s. Tests were performed under commercial conditions to confirm the feasibility of the technique (Nickerson *et al.*, 1983). The factors limiting the practical use of radiation processing of fishery products, and *economic* and commercial feasibility, have been evaluated by Giddings (1984). There is no commercial use of irradiation for fresh fish.

Legal clearance for irradiation of fish and/or shellfish is given in a number of countries including Bangladesh, Thailand, Brazil, Syria, Korea, South Africa and the UK (see Table 10, page 86). Future legislation to allow irradiation of shellfish in the USA is anticipated (Kilgen, 1993)

See also ESR; Fish – dried; Legislation; Microorganisms – relative resistance; Micro-organisms – safety; Nutrition; Seafood; Shrimps and prawns

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Fish – dried

For insect disinfestation, the recommended dose is up to 1 kGy. For reduction in microbial load leading to shelf-life extension, the recommended dose is in excess of 1 kGy.

General

Dried fish is a vital source of *protein* in equatorial countries bordering the Indian and Pacific Oceans. In countries such as Bangladesh, India, Thailand, Indonesia, and the Philippines, drying, combined with salting or smoking, is an important preservation method for fish. However, *post-harvest losses* of dried fish (< 20% moisture) can be high due to *insect* infestation. In addition to insects, at an intermediate moisture level (20–40% moisture), *moulds* are responsible for storage losses.

Insect disinfestation

The most common insects associated with dried fishery products are flesh flies (Sarcophagidae), beetles (*Dermestes*, *Corynestes* and *Necrobia* spp.) and mites (*Lardoglyphus* and *Lyrophagus* spp.) (Dollar, 1989). Irradiation has been considered as an alternative disinfestation treatment to chemical fumigation, or heat treatment, for dried fish (Anon, 1989). The recommended dose varies with the *insect* species, stage of *insect* development, and the moisture content of the product. A dose of 0.3 kGy has been proposed for *insect disinfestation* of dried fish (< 20% moisture); 0.5 kGy for products of intermediate moisture (20–40%).

Pre-irradiation *packaging* is essential to prevent re-infestation by insects. The use of polyethylene film and secondary *packaging* in corrugated boxes has been recommended (Doke, 1990). In addition to protection against *insect* penetration, the film gives good protection against bacterial permeability, water permeability, water vapour transfer and weight loss of the irradiated fish (Hussain *et al.*, 1989).

Guidelines

A Code of Good Irradiation Practice for Insect Disinfestation of Dried Fish and Salted and Dried Fish is published by the International Atomic Energy Agency (ICGFI Document No. 9, 1991)

Shelf-life extension

Radiation doses in excess of 1 kGy are needed to control *mould* growth. A combination of irradiation and sorbic acid have been used to control *insect* infestation and *mould* growth on dried fishery products (Hussain *et al.*, 1989). Radiation doses of 0.5–0.75 kGy were found suitable for keeping sun- or oven-dried fish in good condition for six months.

A combination of salt dip and a radiation dose of 4 kGy is reported to extend the shelf-life of semi-dried fish by three months (IAEA, 1993).

Potential application

Legal clearance for the irradiation of dried fish products is given in a number of countries including Bangladesh, Brazil, Thailand and Vietnam (see Table 10, page 86).

Semi-commercial-scale studies of radiation disinfestation of dried fish have taken place in Bangladesh (Matin *et al.*, 1992) and in Indonesia (Maha, 1992) (and see Table 11, page 98). Disinfestation and reduction in microbiological contamination of dried fish were obtained with a dose of 1 kGy. Favourable reports on product quality, reduction in storage losses and acceptability were judged by market testing. However, the *economic* feasibility of irradiating dried fish requires careful analysis (Anon, 1989).

See also Fish; Insect disinfestation; Market trials

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Flatworm *see* Parasites.

Flavour

Off-flavour development

Irradiation of food can result in the formation of off-flavours and off-odours. Some foods are much more radiation-sensitive than others. All foods and food ingredients will develop flavour changes if exposed to a sufficiently high radiation dose (Fink and Rehmann, 1994).

In *meats* and *poultry*, the off-flavour is described as 'scorched', 'goaty' or 'wet dog'. Its formation is dose dependent; the higher the dose, the more pronounced the sensory changes (Diehl, 1983; Nawar, 1983). Extensive research on the nature of the 'typical irradiation flavour' is reviewed by Nawar (1983). The *lipid* fraction is considered to be a major contributor to the irradiation odour of complex fat-containing foods. However, degradation products of *protein*, e.g. aromatic and sulphur compounds appear to be involved in the production of unpleasant off-flavours. Changes in *fruits* and *vegetables* are related to depolymerization and fragmentation of polysaccharides into sugars, which results in a sweeter or less acid flavour, e.g. *apples*.

Off-flavours are the principal limiting factor to the practical application of irradiation to control *micro-organisms* in certain foods. The threshold dose for detectable off-flavour development limits the maximum dose that can be applied to *meat*; this varies with the *meat* species (see Table 12, page 101). A number of other foods develop off-flavours on irradiation; fatty foods, such as oily *fish* and *dairy products*, *eggs* and beer are particularly sensitive to change. Low-fat foods, e.g. *poultry*, white *fish*, *shrimps* and *spices*, can be treated with a dose that will reduce the numbers of food-borne pathogenic *bacteria* before off-flavour development (Fink and Rehmann, 1994).

Reducing off-flavour formation

The use of low temperatures (below 0°C) reduces off-flavour development (Nawar, 1983). A reduction in *temperature* also increases the resistance of *micro-organisms* to radiation (Diehl, 1983). A dose-temperature combination that yields an acceptable flavour, and at the same time eliminates the *micro-organisms* present, is required.

Irradiation in the absence of air and/or in the presence of antioxidants may prevent the formation of oxidative rancidity in fatty foods and hence flavour changes (Nawar, 1983; Diehl, 1983).

The advantages of using irradiation in combination with other food preservation methods are recognized (Campbell-Platt and Grandison, 1990). Growth of *micro-organisms* is synergistically retarded by *combination treatments*; the result is a reduction in the radiation dose needed to achieve the required microbial kill and this in turn reduces the formation of off-flavours.

See also Combination treatments; Sensory evaluation.

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Flour *see* Cereal grains; Cereal products.

Folic acid (pteroylglutamic acid; vitamin K)

General

Major sources of folic acid include green leaf *vegetables*, such as spinach and *broccoli*, and some *meats*, particularly liver. Chemically, K-vitamins are a group of seven closely-related naphthaquinone derivatives. Folic acid is involved as a coenzyme in reactions involving single carbon unit transfers. Deficiency results in a wide variety of disorders, of which anaemia and infertility are particularly important. Folic acid-dependent reactions are involved in the mechanism of blood clotting, playing an essential role in the synthesis of prothrombin. Deficiency therefore leads to defects in clotting with consequent frequent haemorrhaging into tissues.

Radiation sensitivity

Although radiation-sensitive in simple aqueous solution, e.g. over 90% loss following a dose of 20 kGy (Kishore *et al.*, 1976), folic acid is far more resistant when irradiated in foods. For example, there was no significant loss following nearly 30 kGy irradiation of poultry diet (Richardson *et al.*, 1958) and no more than about 20% losses in *animal diets* given a dose of 25 kGy (Coates *et al.*, 1969).

Although folic acid is amongst the most radiation resistant of the lipid-soluble vitamins (Knapp and Tappel, 1961), rat feeding studies indicated that high dose irradiation (about 50 kGy) destroyed the low levels of vitamin present in *meat*. This was sufficient to produce deficiency symptoms, if the other elements of the diet were free of folic acid. (Mameesh *et al.*, 1962).

See also Vitamins.

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Food components

Dilute aqueous solutions of amino acids, *enzymes*, sugars, *vitamins* and other food components are more sensitive to radiation than when they are irradiated as constituents of foodstuffs (Diehl, 1983). For example, at 0.5 kGy, there was a 50% loss of B vitamins in aqueous solution (0.25 mg/100 ml) and in dried whole egg (0.39 mg/100 g) there was a 5% loss (Diehl, 1990). The radiation resistance of food components increases with increasing concentration of the compound.

Free radical scavengers, such as *ascorbic acid* and cysteine, act as radiation protective substances for food components in foods. Radiolytic effects in foods can be reduced by using *additives*, irradiation at low *temperature* and exclusion of *oxygen*.

See also Additives; Carbohydrates; Lipids; Proteins; Vitamins.

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Formaldehyde

Formaldehyde (HCHO) is one of the radiolysis products formed during the irradiation of sugars, such as sucrose, that are common in many foodstuffs (Steward *et al.*, 1967). Consequently, concern has been expressed because formaldehyde has been shown to be mutagenic, e.g. in the *Ames test* (Connor *et al.*, 1983), at levels that, it is predicted, may be generated in irradiated foods. However, formaldehyde and other aldehydes, ketones and related products occur in many other foods and toxicological studies have not indicated that they cause any problem.

See also Ames test; Toxicology.

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Free radical

A free radical is an electrically neutral atom or molecule with an unpaired electron in the outer orbit. Free radicals are chemically highly reactive and continuously react with substances to form stable products. They are formed during irradiation processing, as well as certain other types of food treatment, such as toasting, frying and freeze drying, and normal oxidation processes in foods.

See also Direct and indirect action of ionizing radiation; Ionization.

Frog legs

Frog legs are frequently contaminated with *Salmonella* due to the inadequacy of conventional chlorination treatment. In frozen frog legs, elimination of this pathogen, and a reduction in viable cell count, can be achieved using a radiation dose of 4 kGy (Nerkar and Lewis, 1982). A slight deterioration in sensory rating occurred with this treatment, but the rate of quality deterioration was less rapid than for non-irradiated frozen samples.

Frog legs are irradiated commercially, in France (see Table 5, page 32), and marketed at the retail level.

A Code of Good Irradiation Practice for the Control of Microflora in Fish, Frog Legs and Shrimps, ICGFI Document No. 10, is published by the International Atomic Energy Agency, Vienna, 1991.

See also Legislation.

Reference

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Frozen foods *see* Direct and indirect action of ionizing radiation; Temperature.

Fruit fly *see* Insects; Insect disinfestation.

Fruit juice *see* Juice.

Fruit and vegetables

Irradiation could be used to treat fresh fruits and vegetables in order to control *insect disinfestation*, delay *ripening* and senescence, and control post-harvest disease (Kader, 1986).

Guidelines

- Code of Good Irradiation Practice for Insect Disinfestation of Fresh Fruits (as a quarantine treatment), ICGFI Document No. 7, Vienna (1991).
- F1355 – Guide for the Irradiation of Fresh Fruits for Insect Disinfestation as a Quarantine Treatment, Annual Year Book of the American Society for Testing and Materials (ASTM) Standards, Vol. 15.07 (1993).
- Irradiation as a Quarantine Treatment of Fresh Fruits and Vegetables – Report of a Task Force, ICGFI Document No. 13, Vienna (1991).

Treatment

It is recommended that treatment of fruits and vegetables should only be used on products of optimum maturity and quality (IAEA, 1985). In addition, fruit and vegetable quality is maintained by:

- Good pre- and post-harvest handling techniques;
- Removal of field heat, dirt and other debris, post-harvest fungicide treatment and coating, if appropriate, and quality sorting;
- Adjustment of existing harvesting, handling, storage and marketing practice, including packaging;
- Knowledge of the post-harvest physiology of produce, varietal susceptibility to irradiation, and criteria for assessing climacteric (if used for delaying ripening);
- Knowledge of the type and level of microbial infection (in order to utilize the appropriate dose).

Product characteristics

The main problem encountered with the irradiation of fruits and vegetables is undesirable changes in *texture*. These may occur below the dose required for the desired technical effect. Radiation induces depolymerization of cellulose, hemicellulose, *starch* and *pectin*, which results in softening. This effect occurs with increasing dose. *Pectin* is particularly sensitive; depolymerization may occur even at doses as low as 0.5 kGy. Soaking fruit in a solution of calcium chloride for 30 minutes prior to irradiation results in rapid firming of fruit after irradiation (Kovacs *et al.*, 1988).

Browning or scalding of fruit skin, internal browning disorders, and increased sensitivity of fruit to chilling, are other possible post-irradiation effects (Barkai-Golan, 1992).

Nutrition

The nutritional losses in fruit and vegetables treated with *ionizing radiation* are affected by dose. Low doses are used to treat products to avoid radiation-induced softening and, thus, losses should be minimal. *Ascorbic acid* may undergo degradation and affect the nutritional value of produce, e.g. potatoes (ACINF, 1986). No reduction in *ascorbic acid* content of fresh produce treated for quarantine security was reported by Jessup *et al.* (1992).

Packaging

Packaging film permeability for gas or water is an important consideration for fruit and vegetables. The shelf-life of produce can be extended by modification of the gas atmosphere in the package in conjunction with low or medium doses of irradiation (Campbell-Platt and Grandison, 1990). Respiration rates are slowed down by elevated levels of carbon dioxide and reduced levels of oxygen in the pack. Rates of deterioration are therefore reduced. In addition, a reduction in radiation-induced losses of vitamin C may be obtained (Langerak, 1978). Sealed *packaging* will act as a water barrier and so will have the advantage of reducing weight loss of fruits and vegetables, although it may stimulate decay by *microorganisms* (Kiss, 1982).

Potential application

Legal clearance for the treatment of specific fruits and vegetables is given in most countries that have legislation governing irradiation (see Table 10, page 86). The *economic* benefits of irradiating a range of fruits and vegetables have been evaluated (IAEA, 1993).

See also Applications; Ascorbic acid; Detection; Legislation; Nutrition; Pectin and cellulose; Ripening and senescence; Starch; Tropical and subtropical fruit.

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G

Gamma radiation *see* Gamma rays; Facilities.

Gamma-rays

Gamma rays are forms of electromagnetic radiation that have very short wavelengths and high energies. This type of radiation consists of quanta, or photons, of energy produced by spontaneous disintegration of the atomic nucleus of *radionuclides*, e.g. cobalt-60.

See also Electromagnetic spectrum; Ionizing radiation; Radionuclide.

Garlic (*Allium sativum*)

For inhibition of sprouting and reduction of weight loss, the recommended dose is 0.05–0.15 kGy.

Treatment

Irradiation is an alternative method to the use of chemicals to inhibit sprouting in garlic (reviewed by Matsuyama and Umeda, 1983; Thomas, 1984). Radiation doses applied shortly after harvest, when bulbs are in the dormancy period, are most effective. Variations in the effectiveness of sprout control, optimal radiation dose, and timing, which have been reported in the literature, may be due to differences in varieties and agronomic histories of garlic bulbs. Temperature of post-irradiation storage will influence shelf-life; ambient temperature storage may exacerbate rotting in irradiated bulbs.

Product characteristics

Throughout a nine-month storage period, there is a reduction in weight loss in irradiated garlic and an increase in marketable bulbs. In commercial marketing trials, garlic irradiated at 0.07 kGy could be stored for nine months at 1–7°C (Nouchpramool *et al.*, 1992; Singson *et al.*, 1992). In Argentina, a dose of 0.05 kGy resulted in a three-month extension of marketable bulbs (Curzio and Croci, 1988).

Irradiation caused no adverse changes in aroma or *flavour* of garlic; irradiated bulbs were superior in external and internal firmness (Curzio and Croci, 1988). There was no effect on levels of dry matter, *carbohydrate* or *ascorbic acid*. A yellowish brown discolouration of the inner bud (growth centre) is a feature of irradiated garlic bulbs but this is not considered to be a problem for fresh consumption or for dehydration (Thomas, 1984).

Potential use

Legal clearance for the irradiation of garlic is given in many countries (see Table 10, page 86). Successful marketing trials of irradiated garlic have been reported in Argentina, China, Cuba, the Philippines and Thailand (see Table 11, page 98). The *economic* benefits of irradiating garlic in China have been established (Zu and Sha, 1993).

See also Inhibition of sprouting.

References

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Gelatin

Gelatin is used in confectionery, *meat* canning and table jellies. Doses of 5–10 kGy, which are needed to improve the microbiological quality of dry gelatin, do not appear to seriously affect the technological or organoleptic properties of the material (Bachman *et al.*, 1974). Although the threshold dose for *flavour* change and decreasing viscosity in gelatin is quoted as 5 kGy, adverse effects may not be detected in food products containing added gelatin, such as canned *meat*.

The effect of *sterilization* doses on the physicochemical properties of dry gelatin is reviewed by Farkas (1988).

See also Legislation; Proteins.

References

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Gelling agents *see* Agar; Alginate; Carrageenan; Gelatin; Pectin and cellulose.

v

Ginger (*Zingiber officinale*)

Sprouting of ginger is inhibited with radiation doses in the range 0.01–0.12 kGy (Thomas, 1988).

See also Spices.

Reference

Thomas, P. (1988) Radiation preservation of foods of plant origin. Part VI. Mushrooms, tomatoes, minor fruits and vegetables, dried fruits and nuts, *CRC Critical Reviews in Food Science and Nutrition*, **26**(4), 313–58.

Gluten *see* Cereal products.

Grain *see* Cereal grains.

Gram *see* Legume.

Grape (*Vitis vinifera*)

Insect disinfestation

Radiation doses in the range 0.2–0.3 kGy, appropriate for disinfestation against the Queensland fruit fly, improved the quality of grapes (Rigney and Wills, 1985). Irradiated *fruit* was firmer with fewer rots than untreated fruit. Grape varieties that require disinfestation for pests other than fruit flies would need to tolerate doses of the order of 0.6–0.75 kGy.

The costs and benefits of irradiation as an alternative method to methyl bromide fumigation for the *insect disinfestation* of grapes have been evaluated (Forsythe and Evangelou, 1993). The adverse effects of *ionizing radiation* on *fruit* quality were considered to limit this application.

Shelf-life improvement

The possibility of using irradiation to inhibit fungal decay in grapes, with the aim of improving shelf-life, has been reviewed by Thomas (1986) and Barkai-Golan (1992). However, doses of the order of 2 kGy, appropriate for the control of *Botrytis* and *Penicillium* spp., affects the quality of the *fruit*. *Fruit* quality is adversely affected by doses in excess of 1 kGy, or even lower, with loss of firmness the main limiting factor. The extent of softening appears to depend on a number of factors, including grape variety, harvest maturity, and post-irradiation storage time and conditions. In addition, there is a risk of skin discolouration and stem darkening in irradiated grapes.

In order to reduce the radiation dose required, and hence adverse changes in *texture*, a combination of radiation and heat, or chemicals, may be used. For example, a *combination treatment* of a hot water dip (50°C for 5 minutes) followed by a radiation dose of 1 kGy, extended ambient and refrigerated shelf-life of grapes (Padwal Desai *et al.*, 1973). The incidence of fungal infection was delayed by 10 days.

Increased juice yield

A dose of 4–5 kGy increased the *juice* yield of grapes by 10–12%, and 0.5 kGy increased yield by 3% (Kiss *et al.*, 1974). However, no radiation-induced increases in *juice* yield were demonstrated in grapes treated with 1–2 kGy (Shirzad and Langerak, 1984).

Potential application

The feasibility of radiation disinfestation for grapes may be limited by the radiation sensitivity of the product. Cheaper and more effective alternatives are available to control fungal decay, e.g. sulphur dioxide (Barkai-Golan, 1992).

See also Fruit and vegetables; Insect disinfestation; Moulds.

References

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Grape must *see* Wine.

Grapefruit

For insect disinfestation (control of Caribbean fruit fly), the recommended dose is 0.15–0.3 kGy.

Treatment

The feasibility of using irradiation as an alternative treatment for infestation of grapefruit by the Caribbean fruit fly has been investigated. A dose of 0.15 kGy provided quarantine security for grapefruit, based on the prevention of adult emergence of the insect. A *combination treatment* of 0.05 kGy, plus 5 days at 1.1°C, gave an equivalent quarantine security (von Windeguth, 1992).

Product characteristics

Treatment of grapefruit with a dose of 0.3 kGy resulted in minimal fruit injury (Spalding and Davis, 1985). Doses in excess of 0.6 kGy caused injury to rind and development of *off-flavours* in the *fruit* (Spalding and Davis, 1985; Moshonas and Shaw, 1984). The radiation sensitivity of the peel of grapefruit limits the application of irradiation for controlling post-harvest fungal decay.

There were no detrimental effects on *ascorbic acid*, sugar, acid levels, or essential peel oil composition, after treatment of the *fruit* with a dose of 0.3 kGy (Moshonas and Shaw, 1984). *Sensory evaluation* of *juice* from grapefruits, treated with 0.75 kGy, showed that the effect of the treatment was not greater than that of storage (Nunez-Selles *et al.*, 1986).

Potential application

There is potential for the use of irradiation for the disinfestation of grapefruit. Successful test marketing of irradiated grapefruit in the USA has been reported (Corrigan, 1993).

See also Citrus fruit; Insect disinfestation.

References

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Gray

The gray (Gy) is the unit of absorbed dose of *ionizing radiation*. It replaces an older unit, the radiation absorbed dose (*rad*). The gray is defined as the dose corresponding to the absorption of 1 joule of energy per kilogram of matter through which the radiation passes.

The kilogray (kGy) is most commonly used as the unit of dose for food irradiation.

1 Gy = 100 rad
1 kGy = 1000 Gy
10 kGy = 1 Mrad (10^6 rad)

Groundnut *see* Nut.

Guar *see* Gums.

Guava (*Psidium guajava*)

The guava is a commonly planted tropical *fruit* that is notable for its high content of *ascorbic acid*. The possibility of using irradiation to delay the *ripening* of guavas, and thus extend the shelf-life, has been examined (Thomas, 1988). Treatment of guavas with a dose of 0.3 kGy resulted in slower rates of *ripening*, providing a shelf-life extension of approximately 5 days, at ambient temperature.

Quarantine treatment of guavas for fruit flies would require a minimum dose of 0.15 kGy.

See also Insect disinfestation; Legislation.

Reference

Thomas, P. (1988) Radiation preservation of foods of plant origin. Part VI. Mushrooms, tomatoes, minor fruits and vegetables, dried fruits and nuts, *CRC Critical Reviews in Food Science and Nutrition*, **26**(4), 313–58.

Guidelines *see* Codes of practice.

Gum arabic *see* Gums.

Gums

The majority of gums are natural polysaccharides. They are used as food ingredients, primarily as rheological agents. Due to the origin of these dry products, they may be contaminated with *micro-organisms*. Irradiation may be used to reduce microbial decontamination.

Guar and carob gums that were treated with radiation doses as low as 0.2–0.5 kGy showed impairment in rheological properties (Farkas, 1988). The viscosities of carob and xanthan gums were substantially reduced by irradiation, in the dry state, with a dose of 10 kGy (Grunewald, 1983). The subsequent viscosity of solutions was reduced far more at high, than at low, temperatures.

The effect of irradiation on powdered guar gum, locust bean gum, gum tragacanth and gum Karaya was investigated at doses less than 10 kGy (King and Gray, 1993). There was a decrease in the viscosity of a 1% solution of guar and locust bean gums, with increasing radiation dose, independent of temperature. For irradiated tragacanth and Karaya gums, the viscosity was unchanged, or slightly higher at doses less than 1 kGy, but above this level viscosity decreased with dose.

Gum arabic (gum acacia) (Blake *et al.*, 1988) and tragacanth are less sensitive to *ionizing radiation* than other gums. Tragacanth gum suffered only a 7% fall in coefficient of viscosity on irradiation at 10 kGy (Jacobs and Simes, 1979). In France and Belgium, there is legal clearance for microbial decontamination of gum arabic using doses of 9–10 kGy (see Table 10, page 86).

See also Carbohydrates; Carrageenan.

References

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G-value

The efficiency of a radiation-induced chemical transformation is expressed as the G-value. This represents the number of molecules reacting or produced by 100 electron volts, or per joule of absorbed energy from *ionizing radiation*.

H

HACCP

HACCP (hazard analysis and critical control point) procedures are regarded as essential components of modern quality assurance programmes for all forms of food processing and preservation, including irradiation. The basic philosophy underlying HACCP is the designing of control requirements into product formulations, processing parameters and operating practices, so as to *prevent* defects, rather than to detect them as in traditional end-product testing and inspection (Baird-Parker and Gould, 1990).

Well-defined steps in HACCP procedures include (Baird-Parker and Mayes, 1989):

1. Identify hazards and understand risks:
   - micro-organisms and toxins;
   - other (e.g. chemical).
2. Rank hazards and risks (severity and frequency).
3. Identify critical control points ('CCPs'):
   - the places where control *must* be assured.
4. Select control and monitoring options:
   - consider effectiveness (utility, reliability, accuracy).
5. Exercise control:
   - implement quality assurance ('QA') procedures.
6. Monitor/verify:
   - implement monitoring systems to ensure that control procedures are operating as intended.

Several guidelines for the operation of HACCP techniques exist (e.g. Chipping Campden Food Research Association, 1987). Benefits of the application of HACCP include:

1. Objective assessment of hazards and risks, from food raw materials, through formulation and processing, to product use.
2. Precise identification and definition of control and monitoring needs.
3. Better and more cost effective control. Concentration of effort on CCPs help to allocate resources appropriately.
4. Reduction in public health spoilage risks.

References

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Half-life

The half-life is the period in which half the radioactive nuclei will decay, e.g. half-life ($T_{1/2}$) of cobalt-60 = 5.3 years. This means that after 5.3 years, only half of original ^{60}Co remains, after 10.54 years, a quarter of the ^{60}Co remains, equivalent to a reduction of activity by 12.324% per year.

See also Radionuclide.

Ham *see* Meat; Nitrite reduction.

Hazard analysis and critical control point *see* HACCP.

Heat *see* Combination treatments; Sensitization of spores to heat.

Herb *see* Spice.

Herbal teas

Herbal teas such as chamomile, mint, hibiscus and rosehip can contain substantial numbers of *bacteria* and *moulds*. Total bacterial counts may be as high as 10^5–10^8 per gram. In South Africa, legal clearance was given, in 1985, for the irradiation of Rooibos tea, following incidents of *Salmonella* contamination.

Low microbiological counts are a requirement in herbal teas and medicinal plants. This is because only maceration and infusion are used in their preparation in order to preserve their volatile, or heat-sensitive, essential oil ingredients. A radiation dose of 7.5–10 kGy reduced the total microbial count of a range of herbal teas and medicinal plants to 10^3 per gram or less (Farkas, 1988). At this dose level, the amount and composition of volatile oils are unchanged.

The feasibility of using irradiation to improve the hygienic quality of chamomile tea (Katušin-Ražem *et al.*, 1985) and ginseng powder (Kwon *et al.*, 1989) has been demonstrated. There is legal clearance for the irradiation of herbal teas in some countries (see Table 10, page 86).

References

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Herpes simplex virus *see* Viruses.

History

Treatment of food with *ionizing radiation* is, except for quick freezing, the only thoroughly novel means for food preservation that has been applied on an industrial scale this century. The first patent, claiming that *X-rays* could be used to inactivate *micro-organisms* in fresh *meat* and meat products, was applied for in the USA in 1921, followed by one granted in France (Wurst, 1930). Later, large work programmes were initiated, particularly at the US Army Laboratories at Natick, Mass. and at the Massachusetts Institute of Technology, in the USA, and at the Atomic Energy Authority Wantage Laboratory and the Low Temperature Research Laboratory at Cambridge, in the UK. These programmes concentrated on the microbiological aspects of food irradiation but also, in the US laboratories, extensive toxicological studies were undertaken in order to evaluate the *safety* of the irradiation of food for human consumption. These programmes, and those in developing countries, have been summarized in publications by Josephson and Peterson (1982, 1983), Urbain (1989) and by Elias and Cohen (1983).

The important aspects of the toxicological *safety* and 'wholesomeness' of irradiated foods were considered at a meeting sponsored by the Food and Agriculture Organization of the United Nations (FAO), the *International Atomic Energy Agency* (IAEA) and the World Health Organization (WHO) held in Brussels in 1961 (FAO, 1963). Studies judged to be necessary to evaluate the *wholesomeness* of irradiated foods were subsequently set out by a FAO/IAEA/WHO Joint Expert Committee ('JECFI') on Irradiated Food, in Rome, in 1964 (WHO, 1966). The view taken was that since the irradiation of foods generated low levels of new chemical species (*'radiolytic products'*), depending to some extent on the nature of the food, establishment of *safety* should be on a food-by-food basis, and similar to that employed for evaluating the safety of food *additives*.

Following a further JECFI meeting in 1976 (WHO, 1977), in which the results of a large number of animal feeding studies were reviewed, unconditional or provisional acceptances were recommended for a wide range of irradiated foods.

In 1980, JECFI considered all further available data on *toxicology* and radiation chemistry, as well as experiences from the feeding of irradiated diets to laboratory animals, to livestock and to immunocompromised human patients.

The committee concluded that the food-by-food approach was unnecessary and that 'the irradiation of any food commodity up to an overall average dose of 10 kGy presents no toxicological hazard; hence, toxicological testing of foods so treated is no longer required' (WHO, 1981). JECFI also concluded that irradiation of food up to a dose of 10 kGy introduces no special microbiological or nutritional problems.

These conclusions and recommendations represented a milestone in the acceptance and progress of food irradiation, and led to the adoption by the Codex Alimentarius Commission, represented by 130 governments, of a Codex General Standard for Irradiated Foods and a Recommended International Code of Practice for the Operation of Radiation Facilities Used for Treatment of Food (Codex, 1984). This has encouraged, to date, 37 countries to approve more than 40 irradiated foods or groups of related foods for consumption, on either a conditional or unconditional basis.

See also Micro-organism – safety; Nutrition; Toxicology.

References

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Wurst, O. (1930) *A Method for Preserving Food*, French Patent 701302.

Hospital diets *see* Sterilization.

Hydrated electron
The hydrated electron ($e^{-}aq$) results from the expulsion of an electron, e.g. from water in a moist foodstuff. It rapidly reacts further to generate negatively charged adducts, e.g. with water.

$$e^{-}aq + H_2O \longrightarrow H_2O^{-}$$

See also Direct and indirect action of ionizing radiation; Ionization; Toxicology.

Hydrocarbons *see* Volatiles.

Hydrocolloid *see* Gums; Gelling agent; Thickening agent.

Hydrogen
Hydrogen may be produced in foods by the activity of some *micro-organisms* and also as a result of irradiation. Hydrogen detectors, based on palladium-coated field-effect transistors, are extremely sensitive and have been evaluated for irradiated food *detection* (Hitchcock, 1994).

See also Detection.

Reference

Hitchcock, C.H.S. (1994) Detection of irradiated foods via determination of hydrogen, *Food Science and Technology Today*, **8**(2), 102–3.

Hydrogen peroxide
Hydrogen peroxide (H_2O_2) is one of the more stable oxidative molecules produced from water in irradiated foods. It is formed indirectly, e.g. from the reaction of two *hydroxyl radicals*.

$$OH\bullet + OH\bullet \longrightarrow H_2O_2$$

See also Direct and indirect action of ionizing radiation; Ionization; Toxicology.

Hydrogen radical
The hydrogen radical ($H\bullet$) is one of the *free radicals* that is formed on irradiation of water in foods. Whilst being highly reactive, and therefore short lived, it can react further with other products from water or with organic compounds of foods to generate new short lived radicals, e.g.:

$$H\bullet + RH \longrightarrow R\bullet + H_2$$

where RH is a food component molecule and $R\bullet$ is an organic free radical derived from it.

See also Direct and indirect action of ionizing radiation; Ionization; Toxicology.

Hydroperoxy radical
Hydroperoxy radicals ($HO_2\bullet$) are highly reactive *free radicals* formed indirectly during the irradiation of water in foods, e.g. by reaction between *hydroxyl radicals* and *hydrogen peroxide* or between *hydrogen radicals* and *oxygen*.

$$OH\bullet + H_2O_2 \longrightarrow H_2O + HO_2\bullet$$
$$H\bullet + O_2 \longrightarrow HO_2\bullet$$

See also Direct and indirect action of ionizing radiation; Toxicology.

Hydroxyl radical
The hydroxyl radical is a *free radical* ($OH\bullet$) formed by the radiolysis of water. The hydroxyl radical is highly reactive and short lived, reacting with other water derived species or with organic components of foods to produce longer lived organic radicals, e.g.:

$$OH\bullet + RH \longrightarrow R\bullet + H_2O$$

where RH is an organic food component and $R\bullet$ is a free radical derived from it.

See also Direct and indirect action of ionizing radiation; Ionization; Toxicology.

I

IAEA *see* International Atomic Energy Agency.

ICGFI *see* International Consultative Group on Food Irradiation.

Identification of irradiated food *see* Detection.

IFFIT *see* International Facility for Food Irradiation Technology.

Immune response

It has been reported that the feeding of irradiated wheat to rats led to suppression of their immune response (Vijayalaxmi, 1978). However, the experiments and arguments of Maier *et al.* (1993) indicated that the effects observed resulted from the nutritional status of the animals in the particular experiments, and were not caused by *radiolytic products* in the irradiated wheat.

See also Toxicology.

References

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Impedance and conductivity

Irradiation may cause changes in the electrical properties of foods. Measurement of direct current to detect these changes may seem attractive, but sensitivity is low, so that alternating current techniques are preferred. With such techniques (variously referred to as conductance, impedance, admittance), ions and charged molecules oscillate in response to the applied field and there are no net changes in the food. Most instruments operate within the frequency range from about 2–10 kHz. At the lower end of this range, capacitance predominates, mainly at or near the electrodes. At the higher end of the range, conductance predominates, mainly reacting to charged species in solution. The overall readings from instruments therefore reflect a combination of these effects (Bolton and Gibson, 1994).

Low dose anti-sprouting irradiation of *potatoes* could be detected by measuring changes in impedance (Hayashi, 1988). The technique involved inserting an electrode into the *potato* and passing an alternating current through it at specific frequencies. The technique was effective during at least six months storage after irradiation.

See also Detection.

References

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Indirect action *see* Direct and indirect action of ionizing radiation.

Induced radioactivity

All foods have some radioactivity due to the presence of naturally occurring *radionuclides*. Irradiation of foodstuffs, with *gamma rays* or *X-rays*, may be expected to induce a low level of radioactivity in foods. In order to prevent induction of further radioactivity, limitations on energy levels, and types of *ionizing radiation*, employed for food irradiation have been established.

The Joint FAO/IAEA/WHO Expert Committee report (WHO, 1981) recommended that the following types of *ionizing radiation* should be permitted for food irradiation (i) *gamma rays* from *radionuclides* cobalt-60 or caesium-137 (ii) *X-rays* from machine sources, below an energy level of 5 MeV (iii) electrons from machine sources, below an energy level of 10 MeV. At these energy levels, measureable levels of radioactivity cannot be induced in food treated with a radiation dose of 10 kGy (ACINF, 1986). Investigation of toxicological effects resulting from the irradiation of foods have concentrated, therefore, solely on the chemical changes that occur.

The likely radiological consequences of consuming irradiated food at short times after irradiation have been evaluated (Terry and McColl, 1992). This study concluded that induced activities in a wide range of foods should be considered below the level judged to be of concern to regulatory authorities.

See also Radioactivity; Toxicology.

References

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Influenza virus *see* Viruses.

Inhibition of sprouting

General

Sprouting during storage is a major physiological cause of spoilage of certain tuber, bulb and root *vegetables*. There are a number of conventional options available to inhibit sprouting. Chemical sprout inhibitors are used, such as isopropyl-n-phenylcarbamate (IPC) or methyl ester of naphthalene acetic acid (MENA) on *potatoes*, and maleic hydrazide or ethepon (2-chloroethyl phosphoric acid) for *onions*. There is public concern about such chemical residues in food. Maintenance of low temperature is an accepted method of sprout inhibition of bulb and tuber crops. Irradiation has been evaluated as an alternative to these traditional methods.

Guidelines

A Code of Good Irradiation Practice for Sprout Inhibition of Bulb and Tuber Crops. ICGFI Document No. 8, Vienna, 1991, is published by the International Atomic Energy Agency, Vienna.

Treatment

Sprouting of *potatoes*, *onions*, *garlic*, shallots, *carrots*, *artichokes*, *sweet potato*, *turnips*, *beetroot*, *ginger*, *chestnuts* and *yams* can be delayed by *ionizing radiation* (Matsuyama and Umeda, 1983). Doses in the range 0.05–0.15 kGy are required for optimal treatment of bulbs and tubers. Cell division and elongation of growing points are inhibited, and thus bud growth. Wound healing is also inhibited. Mechanical damage, incurred during harvest, may therefore lead to increased rotting, due to microbial invasion of the tissue at points of injury. Browning of the inner buds of bulbs and tuber tissue, caused by radiation damage, can be a commercial drawback. Various methods of reducing discolouration have been suggested for individual crops.

Detection

Thermoluminescence can be used to detect low doses of irradiation used to inhibit sprouting (Schreiber *et al.*, 1994). Irradiated *potatoes* may be detected using *impedance* methods.

Potential application

The *economic* feasibility of irradiation as a method of sprout inhibition, in *potatoes* and *onions*, has been demonstrated (IAEA, 1993). Legal clearance for the inhibition of sprouting of *potatoes*, *onions* and *garlic* is given in many countries (see Table 10, page 86).

References

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Injury

Vegetative and spore forms of *micro-organisms* that survive irradiation, as determined by their ability to grow and form a visible colony on a nutritious growth medium, may nevertheless be 'injured'. Injured cells are recognized by their reduced tolerances to secondary stresses such as heat, suboptimal growth temperatures, lowered water activity or pH, and restriction of nutrient supply (Chowdury *et al.*, 1976; Snyder and Maxcy, 1979; Moseley, 1984, 1989).

See also Combination treatments; DEFT; Spores-sensitization to heat.

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Insects

The radiation dose required to kill an insect depends on factors such as age, sex, stage of development, and strain of insect. Factors including temperature, infestation site, food, dose rate and type of radiation are also important (Tilton and Brower, 1983).

Radiation sensitivity of insects must be gauged by determining the lethal or sterilizing effects on the stage of insect present. In general, radiation sensitivity is highest at the egg stage and the lowest at the adult stage of development.

With regard to insect species, fruit flies are the most sensitive of insect pests. The Coleoptera, which includes weevils and beetles, are more radiation resistant. Arachnids, including the mites, have intermediate resistance. Lepidoptera, the moths, are the most resistant of stored product pests (Tilton and Burditt, 1983). It is considered that a minimum dose of 0.15 kGy is an effective quarantine treatment for tephritid fruit flies (Burditt, 1992) and a minimum dose of 0.3 kGy for all other insects (Heather, 1992).

Tephritid fruit flies

A minimum dose of 0.15 kGy is considered to be an effective radiation dose for fruit flies (Burditt, 1992). This dose will prevent adult emergence of the insects but higher doses are required to treat larvae and prevent egg hatch. Doses of the order of 0.6 kGy may be required (Moy *et al.*, 1992). Fruit flies of quarantine importance in many countries include:

Mediterranean fruit fly (Medfly)	*Ceratitis capitata*
Oriental fruit fly	*Dacus dorsalis*
Melon fly	*Dacus cucurbitae*
Queensland fruit fly	*Dacus tryoni* (*Bactrocera tryoni*)
Mango fruit fly	*Dacus occipitalis*
Caribbean fruit fly	*Anastrepha suspensa*
Mexican fruit fly	*Anastrepha ludeus*
Western cherry fruit fly	*Rhagoletis indifferens*

***Codling moth** (Cydia pomonella)*

Produce infested with the codling moth, such as *apples*, *pears*, walnuts and other *fruits* and *nuts*, require exposure to a minimum dose of 0.25 kGy to prevent adult emergence. A radiation dose of the order of 0.5 kGy is recommended to prevent larval emergence (Burditt *et al.*, 1989).

***Mango weevil** (Sternochaetus spp.)*

Irradiation is currently the only disinfection treatment capable of achieving quarantine security against this *mango* pest (Heather, 1992). A minimum dose of 0.3 kGy is recommended for quarantine purposes.

Coleoptera

Produce infested by this group of insects requires a minimum dose of 0.3 kGy to prevent adult emergence. Differences in sensitivity of stored product pests that commonly infest grains, *legumes*, *dried fruits* and *nuts* are tabulated in Brower and Tilton, 1985.

Legume weevils	*Callobruchus* spp.
Granary, rice and maize weevils	*Sitophilus* spp.
Bean weevil	*Acanthoscelides obtectus*
Lesser grain borer	*Rhizopertha dominica*
Larger grain borer	*Prostephanus truncatus*
Grain beetles	*Tribolium* spp.
Khapra beetle	*Trogoderma granarium*
Saw toothed grain beetle	*Oryzaephilus surinamensis*

Dermestes and *Necrobia* spp. come into this category.

Doses required to sterilize Coleoptera vary from 0.07 kGy for *Callobruchus* spp., to 0.15–0.2 kGy for *Rhizopertha dominica*, and to 0.3 kGy for *Trogoderma* spp.

Lepidoptera

A minimum dose of 0.3 kGy is required to prevent adult emergence of Lepidoptera and is recommended for quarantine purposes. A dose of 0.5 kGy, or up to 1 kGy, may be required for sterilization. A range of radiation sensitivities is reported for the Lepidoptera (Brower and Tilton, 1985). In the genus *Ephestia*, for example, the almond moth (*Cadra cautella*) and the rice moth (*Corcyra cephalonica*) are more sensitive than the Indian meal moth (*Plodia interpunctella*). The Angoumois grain moth (*Sitotroga cerealella*) is considered to be the most radioresistant species of all stored-product pests.

Mites (Acaridae)

The mites including the grain mite, *Acarus siro*, the mould mite, *Tyrophagus putrescentiae*, the bulb mite *Rhizoglyus echinopus*, and the redlegged earth mite, *Halotydeus destructor*, are reported to have intermediate sensitivity between the beetles and moths. A radiation dose of 0.3 kGy is recommended for quarantine security (Heather, 1992).

Other insects

Other insects of *economic* and quarantine importance include leaf miners (Diptera), scale insects (Hemiptera-Homoptera) and thrips (Thysanoptera). A dose of 0.3 kGy is recommended for quarantine control (Heather, 1992).

See also Insect disinfestation.

References

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Insect disinfestation

General

Strict quarantine laws, which normally require a defined disinfestation treatment, control the worldwide import of food and agricultural commodities. Current procedures used to satisfy quarantine requirements include heat treatment, cold treatment and fumigation with chemicals, such as methyl dibromide (Sharp, 1992). Concern about the safety of chemical fumigants has prompted a ban on the use of ethylene dibromide by the UK and USA, with a proposed phase-out of methyl dibromide by the year 2000 (Ross and Vail, 1993).

There is extensive literature on the use of *gamma irradiation* as an alternative insect disinfestation procedure. Reviews on research in this field can be found in Moy (1985), IAEA (1991), IAEA (1992). Radiation doses less than 1 kGy are an effective treatment and result in minimal losses in sensory and nutritional quality of foods. The advantage of using irradiation as a disinfestation procedure is that it leaves no toxic residues. Reinfestation can be a problem unless adequate *packaging* materials are used.

Despite the recognition that irradiation is a useful and effective disinfestation process for quarantine and post-harvest uses (IAEA, 1993), there is no widespread commercial use. Although irradiation is not currently approved for import disinfestation by the United States Department of Agriculture, it was authorized as a domestic quarantine treatment for disinfesting *papayas* originating in Hawaii, in February 1989 (Forsythe and Angelou, 1993).

Quarantine standards

Quarantine is a legal means of restricting pests or diseases, which may reside in agricultural commodities, from entering into a non-infested country or area.

Currently probit-9 security level treatment of commodities is required by many countries to satisfy quarantine restrictions. This allows an *insect* mortality rate of no less than 99.9968% in the treated population (no more than 32 survivors in a million insects tested). It has been suggested that the probit-9 concept (used for chemical disinfestation) may be inappropriate for irradiation which produces delayed mortality.

The possibility of a probit-9 security level applied to the prevention of adult emergence, rather than prevention of *insect* eggs and larvae from forming pupae, may be appropriate (Loaharanu, 1992). Lower doses sterilize insects present in foods, and prevent emergence of eggs and larvae as adults, thereby satisfying the quarantine principle. This has the advantage of being more economical and less damaging to the quality of irradiated food. However, this approach means that live, but sterile, insects may be present in the commodity. It also means that quarantine inspectors would have difficulty in differentiating between treated and untreated pests.

Guidelines

- Code of Good Irradiation Practice for Insect Disinfestation of Fresh Fruits (as a quarantine treatment), ICGFI Document No. 7, Vienna (1991).

- F1355 – Guide for the Irradiation of Fresh Fruits for Insect Disinfestation as a Quarantine Treatment, Annual Year Book of the American Society for Testing and Materials (ASTM) Standards, vol. 15.07 (1993).
- Irradiation as a Quarantine Treatment of Fresh Fruits and Vegetables – Report of a Task Force, ICGFI Document No. 13, Vienna (1991).

Choice of dose

It is considered that a minimum dose of 0.15 kGy is an effective quarantine treatment for tephritid fruit flies and a minimum of 0.3 kGy for all other insects (Loaharanu, 1992). These doses provide a probit-9 quarantine security based on the prevention of emergence of normal adult insects.

In commercial practice, most of the product in the consignment will receive a higher dose than the minimum, depending on dose uniformity. If the disinfestation dose required is close to the threshold for damage to the food products (e.g. *mango*, *grapefruit*), the maximum/minimum dose ratio on the package needs to be minimized.

A large number of studies have been carried out on a range of food products to determine optimal treatment levels (Moy, 1985; IAEA, 1991; IAEA, 1992; IAEA, 1993).

Packaging

Irradiation for disinfestation takes place after *packaging*. *Insect* resistant packaging is needed to prevent reinfestation. For *cereal grains* and *pulses*, which are stored for relatively long periods, and are highly susceptible to attack by stored product insects, this is particularly important. Films made from polycarbonate, unplasticized PVC, polyester or polypropylene are more resistant than polyethylene, cellophane or paper (Highland, 1991).

Furthermore, *packaging* of irradiated foods must be designed to withstand whatever handling procedures may be encountered in the distribution system. It may be necessary to take into account *combination treatments*, e.g. the use of heat or fumigation requirements.

Combination treatment

The use of a combination of treatments can reduce the radiation dose required for disinfestation. This will have advantages for product quality (Loaharanu, 1992).

The following treatments in combination with irradiation have been found to increase the mortality of irradiated insects in grain (Tilton and Brower, 1985):

- heat;
- refrigeration;
- chemicals such as fungicides; and
- controlled atmosphere in storage and transit.

A *synergistic* effect of cold treatment in combination with irradiation for Navel *oranges* was demonstrated by Kaneshiro *et al.* (1985). In *grapefruit*, a dose of 0.05 kGy, followed by 5-days cold storage, gave equivalent quarantine security to 0.15 kGy without cold treatment (von Windeguth, 1992). No *synergism* was demonstrated by a combination of heat, chemicals and irradiation, by Moy *et al.* (1992), in a range of *fruit*, because of fruit skin scalding.

Detection

Currently, there is no readily available method for determining whether a food, or an *insect* infesting the food, has been irradiated. A possible method of determining if fruit flies have been irradiated is a reduction in the size of the supraoesphageal ganglion of the fruit fly (Rahman *et al.*, 1992). Recently, Mansour and Franz (1994) developed a simple and field applicable method for identifying whether surviving larvae, in irradiated *fruits*, have been irradiated. This method involved determining the absence of phenoloxidase in irradiated larvae.

Potential application

The costs and benefits of using irradiation as a commercial method of insect disinfestation in a range of products have been evaluated (IAEA, 1993). Legal clearance for the use of the technique for specific products, including grain, *cocoa beans*, fresh *fruit* and *vegetables*, *dried fish*, *dried fruit* and *pulses*, is given in a number of countries (see Table 10, page 86). Marketing trials of irradiated *mango*, *papaya*, *oranges* and *grapefruit* have been successful (see Table 11, page 98).

See also Codes of practice; Facilities; Insects; Legislation; Market trials; Nutrition; Packaging.

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International Atomic Energy Agency

The International Atomic Energy Agency (IAEA) is one of the main sources of information on food irradiation. The Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture and the International Consultative Group on Food Irradiation can be contacted at:

Wagramerstrasse 5
P.O. Box 100
A-1400
Vienna
Austria

Telephone: (+43 1) 2360; Facsimile: (+43 1) 234564

World Wide Web page: http://www.iaea.or.at/programs/ri/

(This page promises to contain Applications in Food and Agriculture. At the time of writing it was under construction.)

See also FAO/WHO/IAEA; JECFI.

International Consultative Group on Food Irradiation

The International Consultative Group on Food Irradiation (ICGFI) was established under the aegis of the FAO, the IAEA and the WHO, in May 1988 (Loaharanu, 1990). The aim of the ICGFI is to facilitate international co-operation in the field of food irradiation. Guidelines and *codes of practice* on all aspects of food irradiation are published by the ICGFI.

The ICGFI has established a Food Irradiation Process Control School (FIPCOS). This provides a training programme, for operators of irradiation facilities which treat food on a commercial basis, and for food inspectors, on proper control procedures for food irradiation processing.

See also Codes of practice; International Atomic Energy Agency.

Reference

Loaharanu, P. (1990) Prospects for international trade in irradiated foods, in *Radiation Physics and Chemistry*, **35** (1–3), 223–31.

International Facility for Food Irradiation

The International Facility for Food Irradiation Technology (IFFIT) is based in Wageningen, The Netherlands. It is sponsored by the FAO, IAEA and the Dutch Ministry of Agriculture and Fisheries, and offers research and training in food irradiation.

Inulin

Inulin is produced in the dahlia tuber, Jerusalem artichoke and chicory roots as a storage *carbohydrate*. The effect of cobalt-60 *gamma rays* on the formation of the major products of inulin has been reported (Bachman and Zegota, 1974). The radiolysis products formed included deoxysugars, *formaldehyde* and organic acids. The radiation-induced degradation of inulin to smaller fragments resulted in the formation of glucose, fructose and sucrose.

Reference

Bachman, S. and Zegota, H. (1974) Physico-chemical changes in irradiated (Gamma ^{60}Co) inulin, in

Improvement of food quality by irradiation, International Atomic Energy Agency, Vienna, 1974, pp. 61–75.

Ionization

Gamma rays emitted from *radionuclides*, and *X-rays* and high-energy *electrons* generated by machine, are all forms of *ionizing radiation*. Such forms of radiation are sufficiently high in energy to cause ionization. Ionization is the creation of positive and negative ions by removal of an orbital electron from an atom (Figure 8). The formation of charged ions caused by the absorption of the energy of *ionizing radiation* in the medium results in chemical and biological effects.

Formation of ions and free radicals

Fast electrons, whether produced by the interaction of *gamma rays* and *X-rays* with matter, or applied directly by an *electron beam*, form positively and negatively charged ions that are extremely unstable, with a lifetime of less than one million millionth of a second (ACINF, 1986). The ions decompose rapidly to form very reactive molecular species known as *free radicals*, which have an unpaired electron in one of their outer orbitals. *Free radicals* react with each other and with unchanged molecules and thus act as intermediaries between ionization and final stable chemical products (the *radiolytic products*). The lifetime of most *free radicals* is short, usually less than one thousandth of a second, but in hard materials, such as bone, much longer lifetimes are possible. *Electron spin resonance*, which is based on the detection of trapped *free radicals*, is a method of identifying irradiated food.

Because fast electrons are produced when *gamma rays* or *X-rays* interact with a medium, and because these electrons cause ionization in the same way as *electron beams* from a machine, the radiation-induced chemical changes in the irradiated medium are the same regardless of the type of radiation used (Diehl, 1990). In any food consisting of a mixture of *protein*, *carbohydrates*, *fats*, *vitamins* and water, very complex chemical reactions occur. The yield of changes in an irradiated substance is defined by the *G-value* (IAEA, 1982). Many changes in foods are initiated by the *free radical* formation in water.

Secondary effects

In water, the major component of food, ionization leads to the production of *hydrogen peroxide* (H_2O_2), a strong oxidizing agent, and *free radicals*, the *hydrogen radical* (H•) and the *hydroxyl radical* (OH•).

Ionization of water:

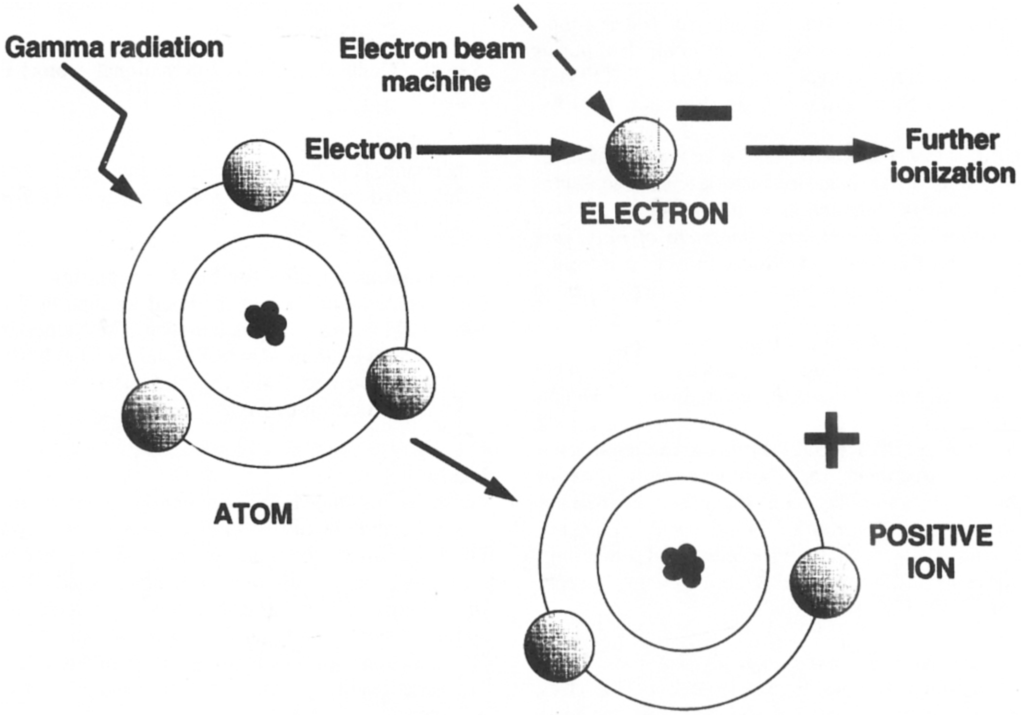

Figure 8 Ionization (courtesy of Leatherhead Food RA, UK). Gamma ray and X-ray photons produce fast electrons by expulsion of orbital electrons from atoms. Electron beam machines are a direct source of fast electrons. These electrons form positively and negatively charged ions in the medium, i.e. ionization. Ionization by photons or electron beams results in similar chemical changes.

1. Formation of ions, which are short lived:
   $H_2O \longrightarrow H_2O^+ + e^-$

2. Reaction of the products of the first process leads to the formation of *free radicals* and *radiolytic products*:
   $H_2O^+ \longrightarrow H^+ + OH\bullet$
   $H_2O + e^- \longrightarrow H_2O^-$
   $H_2O^- \longrightarrow H\bullet + OH^-$
   $OH\bullet + OH\bullet \longrightarrow H_2O_2$

Direct and indirect action of ionizing radiation

Chemical changes may occur as a result of the direct action of *ionizing radiation*. In this case, a sensitive target, e.g. *DNA* in a living cell, is damaged directly by ionizing radiation. In addition, the *radiolytic products* of water may cause indirect changes by reacting with organic molecules, e.g. *protein*, *DNA*, in the food system or the *insects*, *parasites* or *micro-organisms* present. *Dried foods* are more resistant to radiation-induced changes because of the absence of water. Irradiation conditions, including temperature, pH, presence of *oxygen*, will affect the outcome.

Chemical changes, which occur as a result of ionization, may result in death of living cells, e.g. *micro-organisms*. In the case of food, these changes may be beneficial, e.g. *inhibition of sprouting* of bulbs and tubers, *ripening* delay of *fruits*. Modification of *food components* may lead to deterioration, or improvement, in the functional and organoleptic properties of foods.

Radiation-induced changes have been examined in order to ensure the *safety* of irradiated food. The chemical changes produced in food by *ionizing radiation* are, in general, much less severe than, for example, in cooking and heating food. The chemical substances formed as a result of ionization are nearly all substances that can also be found either as natural constituents of food or as a result of conventional food treatment (ACINF, 1986).

See also Applications; Direct and indirect action of ionizing radiation; Detection; Dose rate; Food components; Hydrated electron; Hydroperoxy radical; Ionizing radiation; Toxicology.

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Ionizing radiation

Nature and forms of ionizing energy

Ionizing radiation of primary interest for food preservation includes *gamma rays*, *X-rays* and high-energy *electrons*. The nature and forms of ionizing energy, with specific reference to food irradiation can be found in IAEA (1982) and Diehl (1990).

Gamma rays and *X-rays* are forms of electromagnetic radiation (Figure 1, page 49). This type of radiation consists of quanta, or photons, of energy transmitted in the form of wave motion. The high energy is due to the short wavelength of *gamma rays* and *X-rays*; in the case of *electrons* it is due to their very high velocity. Ionizing radiation, in contrast to microwave, infra-red and ultra-violet radiation, is sufficiently high in energy to cause *ionization*.

Photons and high-energy electrons are different forms of radiation with very different penetrative properties (Sharpe, 1990). However, the effect of photons incident on low atomic number materials (e.g. carbon, hydrogen, oxygen) is to produce a cascade of secondary electrons (fast electrons) in the absorbing material. It is the secondary electrons, rather than the primary photons, that transfer most energy to the absorbing material. The energy of the ionizing radiation absorbed by the medium (i.e. the radiation dose) causes *ionization*, which can bring about chemical and biological changes. The unit of absorbed dose is called the *gray* (Gy), and is defined as an energy deposition of 1 joule/kg. A dose of 10 kGy is equal to the amount of heat required to raise the *temperature* of water by 2.4°C.

In the energy ranges used for food irradiation, both types of radiation produce the same chemical and biological effects. However, minor differences may be observed because the *dose rate* from an electron beam machine may be many orders of magnitude higher than photon sources.

Gamma-rays and X-rays

Gamma ray sources for food processing applications are the *radionuclides*, cobalt-60 or caesium-137; *X-rays* are produced by machine.

Gamma rays and *X-ray* photons have no mass or charge. *Gamma rays* originate within atomic nuclei and have definite discrete energies. *X-rays* originate from changes in the electron orbits of atoms and usually have a broad spectrum of energies. The energy level of *gamma rays* from radioactive sources or *X-rays* from electrical machines is expressed in *electron volts* (eV). The use of *gamma rays* from the *radionuclides* cobalt-60 or caesium-137, or *X-rays* of energy not greater than 5 MeV, is recommended for food (Codex, 1984).

For low atomic number materials (e.g. carbon, hydrogen, oxygen), the main form of interaction with photons of energies between 200 keV and 20 MeV is a process of inelastic scattering or Compton scattering (Sharpe, 1990; Diehl, 1990). In Compton scattering, part of the energy of the photon is transferred to an electron that is ejected from an atom. The energetic electron transfers its energy to the medium in a series of interactions with orbital electrons, producing paths of further *ionization* (see Figure 8, page 78). The photon gives up only part of its energy and is deflected with a longer wavelength to go on to further Compton events. The process continues until all the energy has been transferred to the electrons.

Two other processes by which photons can transfer energy are the photoelectric effect and pair production. These processes only become important at energies lower or higher, respectively, than used in radiation processing (Sharpe, 1990).

Gamma rays and *X-rays* travel very large distances in dense media and are difficult to absorb completely. Photons in the energy range used for food irradiation show approximately exponential decrease of absorbed dose with depth (Figure 5, page 56). The highly penetrating characteristics of these types of radiation means that they can be used to treat food in large containers, e.g. *spices* in 50 kg drums.

High-energy electrons

High-energy electrons are produced by heating a tungsten element and accelerating the emitted electrons inside an evacuated envelope by applying a high voltage. This is the basis of electron beam machines (Figure 3, page 54). It is recommended that electrons generated from machine sources operated at energy levels below 10 MeV are suitable for food irradiation (Codex, 1984).

Accelerated electrons are high in energy and are directly ionizing. They lose energy in a continuous series of interactions with orbital electrons in the absorbing medium. Energy transferred to the electrons causes *ionization*.

Typical dose depth curves for electrons are shown in Figure 6, page 56. Unlike photons, high energy electrons have a finite range in water, approximately 5 mm per MeV (Sharpe, 1990). They penetrate only short distances in food, e.g. 10 MeV electrons can penetrate food typically about 4 cm thick (Figure 7, page 56). These electrons, because of their charge, react with the electrostatic field of the medium, which rapidly slows them down and limits their penetration.

See also Direct and indirect action of ionizing radiation; Electromagnetic spectrum; Facilities; Induced radioactivity; Ionization; Radionuclide; X-rays.

References

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Sharpe, P.H.G. (1990) Dosimetry for food irradiation, in *Food Irradiation and the Chemist* (eds D.E. Johnston and M.H. Stevenson), Spec. pub. No. 86, Royal Society of Chemistry, pp. 109–23.

Irradiation facilities *see* Facilities.

Isoascorbic acid *see* Ascorbic acid.

Isotope *see* Radionuclide.

J

JECFI

Reports of a Joint FAO/IAEA/WHO Expert Committee on Food Irradiation (JECFI) have been central to the international acceptance and progress of food irradiation:

- Report of a Joint FAO/WHO/IAEA Expert Committee, The technical basis for legislation on irradiated food, WHO Technical Report Series No. 316 (1966).
- Report of a Joint FAO/WHO/IAEA Expert Committee, Wholesomeness of Irradiated Foods, WHO Report Series, No. 604 (1977).
- Report of a Joint FAO/WHO/IAEA Expert Committee, Wholesomeness of irradiated food, WHO Technical Report Series, No. 659 (1981).

See also FAO/IAEA/WHO; History.

Juice

Shelf-life improvement

Early work on the irradiation of fruit juice, which was aimed at improving shelf-life, demonstrated that radiation doses in excess of 10 kGy were needed to prevent fermentation by *yeasts*. *Enzymes* were not inactivated by the treatment. The use of high radiation doses is limited by the formation of undesirable *flavour* and *colour* changes in fruit juices (Diehl, 1983). *Off-flavour* thresholds are quoted as 2–3 kGy for *apple* juice and 1 kGy for *grape* juice. The acceptability of irradiated *orange* juice decreased with doses above 0.6 kGy (Mitchell *et al.*, 1991).

The formation of *off-flavours* may be inhibited in irradiated fruit juices by the addition of 0.1% sorbic acid (Thakur and Arya, 1993). In *orange* juice, which was heat pasteurized prior to irradiation at 10 kGy, the addition of sorbic acid inhibited *off-flavour* production, and reduced the rate of browning and *ascorbic acid* loss. No detrimental effects on sensory quality were demonstrated in *grape* juice irradiated at 15–20 kGy in the frozen state (Gaisch and Kaindl, 1962).

Combination treatments can be used to treat fruit juices to improve both microbiological and sensory quality. *Apple* and *pear* juice concentrates were treated with heat at 50°C, for 10 minutes, and a radiation dose of 4 kGy (Kaupert *et al.*, 1981). Long-term storage of the products at 25°C was obtained, with no contaminating flora observed in 150-days storage. *Colour* changes and browning were detected in the concentrates, but the *flavour* scores were unaffected.

The use of irradiation is unlikely to be economically feasible in view of existing commercial methods of preservation of fruit juice, such as aseptic packaging.

Increased juice yield

There are conflicting results on the effect of irradiation on fruit juice yield. A dose of 4–5 kGy increased the juice yield of *grapes* by 10–12%, and at 0.5 kGy increased it by 3% (Kiss et al., 1974). However, other studies have reported a decrease in juice yield. A reduction of 11% in juice yield in *lime* fruit pulp irradiated with a dose of 3 kGy was reported (Nyambati and Langerak, 1989). There is evidence for a decrease in juice yield from *apples* and *grapes*, of the order of 5%, at 0.6 kGy (Mitchell *et al.*, 1991); juice yield from *oranges* was unaffected.

See also Legislation.

References

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Nyambati, M.G. and Langerak, D.S. (1989) The effect of gamma radiation and pectolytic enzymes on chemical quality, organoleptic quality and yield of juice from lime fruit pulp, *Tropical Science*, **29**(2), 119–25.

Thakur, B.M. and Arya, S.S. (1993) Effect of sorbic acid on irradiation-induced sensory and chemical change in sweetened orange juice and mango pulp, *International Journal of Food Science and Technology*, **28**, 371–6.

K

Karaya gum *see* Gums.

Kiwifruit (*Actinidia deliciosa*)

The use of radiation doses below 1 kGy, has potential for *insect disinfestation* of kiwifruit (CAST, 1989; Kaneshiro *et al.*, 1985).

The microbial quality of frozen kiwifruit was improved using a dose of 1 kGy (Lodge *et al.*, 1985). Physical, chemical and sensory properties of the product were unaffected by the treatment.

See also Fruit and vegetables.

References

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L

Labelling

General

The Joint FAO/IAEA/WHO Expert Committee (1981) concluded that it was not necessary on scientific grounds to label irradiated foods. However, it is widely recognized that labelling is necessary to inform the consumer that the product has been irradiated and to indicate the purpose.

In general, countries that issue regulations on food irradiation require that foods processed by radiation, and packaged for retail sale, should be labelled by the statement 'irradiated' or 'treated with ionizing radiation' or 'treated with ionizing energy'. 'Protégé par ionisation' has been used in France. The label must be prominently displayed in close proximity to the name of the product (IAEA, 1993). In a minority of countries, e.g. South Africa and China, labelling is not required at the retail level. The use of the green food irradiation symbol (Radura symbol) is internationally recognized (Figure 9). The Radura symbol is required in addition to a worded statement in some countries, such as the USA and The Netherlands.

On retail labels, an additional statement, which explains the specific purpose for which the irradiation has been used, e.g. to ensure hygienic quality, is recommended (IAEA, 1993). Positive consumer attitudes to informative labelling have been demonstrated (Bruhn, 1995).

Codex recommendations

Codex 1991 recommendations for labelling irradiated food are as follows:

1. The label of a food which has been treated with irradiation shall carry a written statement indicating that treatment in close proximity to the name of the food. The use of the international food irradiation symbol (see Figure 9) is optional, but when it is used, it shall be in close proximity to the name of the food.

Figure 9 Radura symbol. The green Radura symbol indicates that a food product has been treated with ionizing radiation.

2. When an irradiated product is used as an ingredient in another food, this shall be so declared in the list of ingredients.
3. When a single ingredient is prepared from a raw material which has been irradiated, the label of the product shall contain a statement indicating the treatment.

Irradiated ingredients

Some national authorities accept that labelling statements are not required on non-irradiated packaged foods that contain irradiated minor ingredients, such as *spices*. This is the case in The Netherlands, USA and France. It is not the case in the UK, where the regulations state that indication of the treated ingredient shall be accompanied by the words 'irradiated' or 'treated by ionizing radiation'.

In addition to the need to label irradiated ingredients in the UK, labelling also applies to foods sold in catering establishments including take-away establishments (The Food Labelling (Amendment) Irradiated Food Regulations 1990, SI 2489).

Practical aspects of labelling

Non-uniformity of countries' labelling regulations may act as barriers to trade and could increase costs, if different labels are required for transportation to different countries (Pothisiri, 1989). Clearly, harmonization of labelling standards is required on an international basis.

Uniform labelling would aid consumer education on food irradiation. The specific words chosen for the label promote consumer acceptance. The benefits of labelling foods e.g. 'irradiated to extend shelf-life' or 'irradiated to control microbes' have been discussed by Bruhn (1995). An indication of the positive benefits of the treatment may act as a balance to the possibility that labelling puts irradiated foods at a disadvantage, compared with other food preservation methods.

See also Consumer attitudes.

References

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Lactobacillus

General

Lactic acid bacteria, including *Lactobacillus*, *Enterococcus* and *Streptococcus* species (e.g. *E. faecalis*) are Gram-positive facultatively anaerobic *bacteria* that often contaminate *meat* and *poultry*. They compete poorly with the normal Gram-negative spoilage flora that includes fast-growing oxygen-dependent psychrotrophic *bacteria* such as *Pseudomonas fragi* and, at higher temperatures, members of the Enterobacteriaceae.

However, if the Gram-negative flora is suppressed, e.g. by vacuum or 'modified atmosphere' packaging, or inactivated, e.g. by irradiation, then a (safe), slower souring 'lactic spoilage' may predominate.

Radiation resistance

The predominance of the lactic acid bacteria may occur following irradiation because some of these organisms are more radiation tolerant than the more sensitive of the fast-growing Gram-negative *micro-organisms*. For example, lactobacilli had *D-values* in *chicken* between 0.40 and 0.59 kGy under various conditions of *packaging* (Patterson, 1988 and see Table 18, page 131) and *D-values* of *Entercoccus (Streptococcus) faecalis* ranged from 0.65 to as high as 0.70 kGy.

Following a dose of 3 kGy, and storage at 4°C, lactobacilli became the predominant flora of vacuum-packed ground *beef* (Holzapfel and Niemand, 1985). Irradiation of cut *vegetables* used as 'soup greens' at doses up to 2 kGy delayed spoilage from about 1 to about 4 days at 10°C by reducing the numbers of the Gram-negative flora in favour of the lactic bacteria (Langerak and Damen, 1978).

References

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Langerak, D.I. and Damen, G.A.A. (1978) Influence of irradiation on the keeping quality of pre-packed soup greens stored at 10°C, in *Food Preservation by Irradiation*, Vol. 1., pp. 275–82, International Atomic Energy Agency, Vienna.

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Lamb *see* Meat.

Legislation

A list of clearances of irradiated food by country is given in Table 10. Under the Treaty of Rome, prohibition of irradiated food in countries in the European Community was not possible from 1993. However, regulation of food irradiation in EC countries is unharmonized. There is as yet no EC Directive on food irradiation. Certain countries such a Belgium, France, The Netherlands, Portugal and the UK are in favour of a directive on some irradiated food products, whereas countries such as Denmark, Germany and Luxembourg oppose it.

UK regulations include:

- The Food (Control of Irradiation) Regulations 1990, SI 2490, HMSO 1991.
- Guidelines on the Food (Control of Irradiation) Regulations, 1990, HMSO 1991.
- The Food Labelling (Amendment) (Irradiated Food) Regulations 1990, SI 2489, HMSO 1991.

Legume

Members of the Leguminosae family are consumed as dry mature seeds (grain legumes or pulses) and include:

Lentil (*Lens esculenta, L. culinaris*)
Green gram, mung bean (*Phaseolus aureus, Vigna radiata*)

Table 10 List of clearances of irradiated foods by country (September 1995). Published with permission of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Argentina				
Asparagus	1	Unconditional	02/08/90	2
Fruits (dried)	2	Unconditional	09/12/92	1
Garlic	6	Unconditional	03/04/87	0.15
Mushrooms	1	Unconditional	02/08/90	3
Onions	6	Unconditional	03/04/87	0.15
Potato	6	Unconditional	03/04/87	0.15
Spices	3	Unconditional	09/12/90	30
Spices	3	Unconditional	09/12/90	10
Strawberry	5	Unconditional	03/04/87	2.5
Vegetables (dried)	2	Unconditional	09/12/90	1
Bangladesh				
Chicken	3	Unconditional	29/12/83	7
Condiments	2	Unconditional	29/12/83	1
Condiments	3	Unconditional	29/12/83	10
Fish	3	Unconditional	29/12/83	2.2
Fish (dried)	2	Unconditional	29/12/83	1
Fish products	3	Unconditional	29/12/83	2.2
Frog legs	3,5	Conditional	29/12/83	7
Mango	1,2	Unconditional	29/12/83	1
Onions	6	Unconditional	29/12/83	0.15
Papaya	1,2	Unconditional	29/12/83	1
Potato	6	Unconditional	29/12/83	0.15
Pulses	2	Unconditional	29/12/83	1
Rice	2	Unconditional	29/12/83	1
Shrimp	3,5	Conditional	29/12/83	5
Spices	2	Unconditional	29/12/83	1
Spices	3	Unconditional	29/12/83	10
Wheat	2	Unconditional	29/12/83	1
Wheat products	2	Unconditional	29/12/83	1
Belgium				
Garlic	6	Conditional	16/10/80	0.15
Gum arabic	3	Conditional	23/09/83	10
Herbs	3	Conditional	29/09/83	10
Onions	6	Conditional	16/10/80	0.15
Potato	6	Conditional	16/07/80	0.15
Shallot	6	Conditional	16/10/80	0.15
Shrimp	3	Conditional	30/11/88	5
Spices	3	Conditional	29/09/83	10
Strawberry	5	Conditional	16/07/80	3
Tea, herbal	3	Conditional	30/11/88	10
Vegetables (dried)	3	Conditional	29/09/83	10
Brazil				
Avocado	2	Unconditional	25/09/89	1
Banana	2	Unconditional	25/09/89	1
Beans	2	Unconditional	08/03/85	1
Fish	5	Unconditional	08/03/85	2
Fish (dried)	2	Unconditional	08/03/85	2
Fish products	5	Unconditional	08/03/85	2
Guava	2	Unconditional	25/09/89	1
Lemon	2	Unconditional	25/09/89	1
Maize	2	Unconditional	08/03/85	0.5
Mango	2	Unconditional	25/09/89	1
Melon	2	Unconditional	25/09/89	1
Onions	6	Unconditional	08/03/85	0.15
Orange	2	Unconditional	25/09/89	1
Papaya	2	Unconditional	08/03/85	1
Persimmon	2	Unconditional	25/09/89	1
Pineapple	2	Unconditional	25/09/89	1
Potato	6	Unconditional	08/03/85	0.15
Poultry	3	Unconditional	08/03/85	7
Rice	2	Unconditional	08/03/85	1
Spices	3	Unconditional	08/03/85	10
Strawberry	5	Unconditional	08/03/85	3
Tomato	2	Unconditional	25/09/89	1
Wheat	2	Unconditional	08/03/85	1
Wheat flour	2	Unconditional	08/03/85	1
Canada				
Herbs	3	Unconditional	03/10/84	10
Onions	6	Unconditional	25/03/65	0.15
Potato	6	Unconditional	09/11/60	0.15
Spices	3	Unconditional	03/10/84	10
Vegetable seasonings (dried)	3	Unconditional	03/10/84	10
Wheat	2	Unconditional	25/02/69	0.75
Wheat flour	2	Unconditional	25/02/69	0.75
China				
Apple	5	Unconditional	30/09/88	0.4
Apricot	2	Unconditional	23/02/94	1
Cereal grains	2	Unconditional	30/11/84	0.45
Chicken (spiced)	3	Unconditional	23/02/94	8
Cooked meat products	3	Unconditional	23/02/94	6
Fruits (dried)	2	Unconditional	23/02/94	1
Garlic	6	Unconditional	30/11/84	0.1
Litchi	2	Unconditional	23/02/94	0.5
Mandarin	5	Unconditional	23/02/94	0.1
Mushrooms	1	Unconditional	30/11/84	1
Onions	6	Unconditional	30/11/84	0.15
Peanut	2	Unconditional	30/11/84	0.4
Pork	7	Unconditional	23/02/94	0.65
Potato	6	Unconditional	30/11/84	0.2
Sausages (Chinese)	3	Conditional	30/11/84	8
Sweet potato wine	10	Unconditional	23/02/94	4
Tomato	5	Unconditional	23/02/94	4
Costa Rica Note: All clearances in Costa Rica are specified on the basis of average absorbed dose.				
Chicken	3	Unconditional	07/07/94	7
Cocoa beans	2	Unconditional	07/07/94	1
Cocoa beans	3	Unconditional	07/07/94	5
Condiments	2	Unconditional	07/07/94	1

Explanations for Codes: 1. Delay ripening/physiological growth. 2. Disinfestation. 3. Microbial control. 4. Quarantine treatment. 5. Shelf-life extension. 6. Sprouting inhibition. 7. Trichina/parasite control. 8. Sterile meals for hospital patients. 9. Sterilization. 10. Unstated.

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Condiments	3	Unconditional	07/07/94	10
Fish	3	Unconditional	07/07/94	2.2
Fish (dried)	2	Unconditional	07/07/94	1
Fish products	2	Unconditional	07/07/94	1
Fish products	3	Unconditional	07/07/94	2.2
Legumes	2	Unconditional	07/07/94	1
Mango	2,5	Unconditional	07/07/94	1
Onions	6	Unconditional	07/07/94	0.15
Papaya	2	Unconditional	07/07/94	1
Potato	6	Unconditional	07/07/94	0.15
Rice	2	Unconditional	07/07/94	1
Strawberry	5	Unconditional	07/07/94	3
Wheat	2	Unconditional	07/07/94	1
Wheat products	2	Unconditional	07/07/94	1
Croatia				
Cereal grains	2	Unconditional	21/06/94	1
Cereal muesli	2	Unconditional	21/06/94	1
Cereal muesli	3	Unconditional	21/06/94	10
Egg (frozen)	3	Unconditional	21/06/94	3
Egg powder	3	Unconditional	21/06/94	3
Egg products (frozen)	3	Unconditional	21/06/94	3
Enzyme preparations	3	Unconditional	21/06/94	10
Fish	3	Unconditional	21/06/94	5
Frog legs	3	Unconditional	21/06/94	8
Fruit	1,3	Unconditional	21/06/94	3
Fruit (dried)	2	Unconditional	21/06/94	1
Fruit (dried)	3	Unconditional	21/06/94	10
Fruit juices (frozen)	5	Unconditional	21/06/94	4
Garlic	6	Unconditional	21/06/94	0,5
Gum arabic	3	Unconditional	21/06/94	10
Meat (fresh)	5	Unconditional	21/06/94	3
Meat (frozen)	3	Unconditional	21/06/94	7
Mushrooms (dried)	2	Unconditional	21/06/94	1
Mushrooms (dried)	3	Unconditional	21/06/94	10
Onions	6	Unconditional	21/06/94	0.5
Pork carcasses or parts	7	Unconditional	21/06/94	1
Potato	6	Unconditional	21/06/94	0.5
Poultry (fresh)	3	Unconditional	21/06/94	3
Poultry (frozen)	3	Unconditional	21/06/94	7
Roots	6	Unconditional	21/06/94	0.5
Sausages (dry, semi-dry)	3	Unconditional	21/06/94	5
Seafood	3	Unconditional	21/06/94	5
Spices	3	Unconditional	21/06/94	30
Sterile meals	9	Unconditional	21/06/94	45
Tea, herbal	3	Unconditional	21/06/94	10
Tubers	6	Unconditional	21/06/94	0.5
Vegetables	1,3	Unconditional	21/06/94	3

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Vegetables (dried)	2	Unconditional	21/06/94	1
Vegetables (dried)	3	Unconditional	21/06/94	10
Cuba				
Animal blood (dried)	2	Conditional	01/01/90	2
Avocado	1	Conditional	01/08/92	0.25
Bacon	3	Conditional	01/03/91	4
Casings (hog)	3	Conditional	01/10/88	7
Cocoa (dehydrated)	2	Unconditional	01/01/89	2
Cocoa beans	2	Unconditional	01/01/88	0.5
Fish (dried)	2	Unconditional	01/05/93	1
Garlic	6	Unconditional	01/04/87	0.08
Mango	1	Conditional	01/07/92	0.75
Meat	3	Conditional	01/08/91	5
Meat products	3	Conditional	01/03/90	4
Onions	6	Unconditional	01/04/87	0.06
Potato	6	Unconditional	01/04/87	0.1
Seafood	5	Conditional	01/01/91	3
Sesame seed	2	Unconditional	01/10/93	2
Spices	2	Unconditional	01/08/90	5
Czech Republic				
Foods (dehydrated)	3	Conditional	24/08/92	10
Spices	3	Conditional	24/08/92	10
Denmark				
Herbs	3	Unconditional	23/12/85	15
Spices	3	Unconditional	23/12/85	15
Finland				
Spices	3	Unconditional	13/11/87	10
Sterile meals	9	Unconditional	13/11/87	100
France				
Animal blood (coagulated)	3	Unconditional	04/12/86	10
Animal blood (liquid)	3	Unconditional	06/03/87	10
Animal blood plasma (dried)	3	Unconditional	04/12/86	10
Animal blood products (dried)	3	Unconditional	04/12/86	10
Apricot (dried)	3	Unconditional	25/07/91	6
Bovine colostrum	3	Unconditional	16/01/92	10
Camembert cheese	3	Unconditional	23/03/93	3.5
Casein, caseinates	3	Unconditional	21/07/91	6
Cereal flakes	3	Unconditional	16/06/85	10
Cereal germ	3	Unconditional	17/05/85	10
Cereal grains	3	Unconditional	16/06/85	10
Cereal muesli	3	Unconditional	16/06/85	10
Chicken	3	Unconditional	01/09/90	5
Chicken meat (mechanically separated)	3	Unconditional	23/03/85	5
Dates	3	Unconditional	25/07/91	6

Explanations for Codes: 1. Delay ripening/physiological growth. 2. Disinfestation. 3. Microbial control. 4. Quarantine treatment. 5. Shelf-life extension. 6. Sprouting inhibition. 7. Trichina/parasite control. 8. Sterile meals for hospital patients. 9. Sterilization. 10. Unstated.

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Egg products	3	Unconditional	17/11/90	4
Figs (dried)	3	Unconditional	25/07/91	6
Frog legs	3	Unconditional	08/05/88	8
Fruit (dried)	2	Unconditional	13/01/88	1
Garlic	6	Unconditional	12/07/84	0.15
Gum arabic	3	Unconditional	16/06/85	9
Herbs	3	Unconditional	22/05/90	10
Onions	6	Unconditional	12/07/84	0.15
Potato	6	Unconditional	12/12/72	0.15
Poultry	3	Unconditional	01/09/90	5
Raisins	3	Unconditional	25/07/91	6
Rice flour	3	Unconditional	13/11/88	5
Rice meal	3	Unconditional	13/11/88	5
Shallot	6	Unconditional	12/07/84	0.15
Shrimp	3	Unconditional	10/10/90	5
Spices	3	Unconditional	10/02/83	11
Strawberry	5	Unconditional	06/01/89	3
Vanilla	3	Unconditional	28/01/86	11
Vegetables(dried)	10	Unconditional	16/06/85	10
Vegetables(dried)	2	Unconditional	13/01/88	1
Hungary				
Cherries	5	Conditional	15/04/82	2.5
Cherries, sour (canned)	10	Conditional	20/02/84	0.2
Chicken (frozen)	3	Conditional	03/10/83	4
Currants, red	5	Conditional	15/04/82	2.5
Grapes	5	Conditional	15/04/82	2.5
Mixed dry ingredients	3	Conditional	20/11/76	5
Mushrooms	1	Conditional	15/04/82	3
Mushrooms (Agaricus spp.)	1	Conditional	15/04/82	2.5
Onions	6	Unconditional	23/06/82	0.2
Pear	1	Conditional	24/01/83	1
Potato	6	Conditional	28/01/83	0.1
Spices	3	Unconditional	19/08/86	6
Strawberry	5	Conditional	15/04/82	2.5
India				
Onions	6	Unconditional	09/08/94	0.09
Potato	6	Unconditional	09/08/94	0.15
Seafood (frozen)	3	Conditional	02/03/91	6
Shrimp	3	Conditional	02/03/91	6
Spices	3	Unconditional	09/08/94	14
Indonesia				
Beans	3	Unconditional	10/02/95	5
Bulbs	6	Unconditional	29/12/87	0.15
Cereal grains	2	Unconditional	29/12/87	1
Fish (dried)	5	Unconditional	10/02/95	5
Frog legs (frozen)	3	Unconditional	10/02/95	7
Garlic	6	Unconditional	29/12/87	1
Onions	6	Unconditional	29/12/87	1
Potato	6	Unconditional	29/12/87	1
Pulses	3	Unconditional	10/02/95	5
Roots and tubers	6	Unconditional	29/12/87	0.15

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Shrimp (frozen)	3	Unconditional	10/02/95	7
Spices	3	Unconditional	29/12/87	10
Iran				
Spices	3	Unconditional	09/07/90	10
Israel				
Animal feed	3	Unconditional	17/02/87	15
Cereal grains	2	Unconditional	17/02/87	1
Cocoa beans	2	Unconditional	17/02/87	1
Coffee beans	2	Unconditional	17/02/87	1
Edible seeds	2	Unconditional	17/02/87	1
Fruit	2	Unconditional	17/02/87	1
Mushrooms	5	Unconditional	17/02/87	3
Nuts	2	Unconditional	17/02/87	1
Poultry	3	Unconditional	17/02/87	7
Pulses	2	Unconditional	17/02/87	1
Spices	3	Unconditional	17/02/87	10
Strawberry	5	Unconditional	17/02/87	3
Vegetable seasonings (dried)	2,3	Unconditional	17/02/87	10
Vegetables	2	Unconditional	17/02/87	1
Vegetables (dried)	3	Unconditional	17/02/87	10
Italy				
Garlic	6	Unconditional	30/08/73	0.15
Onions	6	Unconditional	30/08/73	0.15
Potato	6	Unconditional	30/08/73	0.15
Japan				
Potato	6	Unconditional	30/08/72	0.15
Korea, Rep. of				
Chestnuts	2	Unconditional	16/10/87	0.25
Enzyme preparations	3	Unconditional	19/05/95	7
Fish powder	3	Unconditional	14/12/91	7
Garlic	6	Unconditional	14/12/91	0.15
Meat (dried)	3	Unconditional	14/12/91	7
Mushrooms	2	Unconditional	16/10/87	1
Mushrooms (dried)	2	Unconditional	16/10/87	1
Onions	6	Unconditional	16/10/87	0.15
Potato	6	Unconditional	28/09/87	0.15
Red pepper paste powder	3	Unconditional	14/12/91	7
Shellfish powder	3	Unconditional	14/12/91	7
Soy sauce powder	3	Unconditional	14/12/91	7
Soybean paste powder	3	Unconditional	14/12/91	7
Spices	3	Unconditional	13/09/88	10
Starch	3	Unconditional	14/12/91	5
Sterile meals	9	Unconditional	19/05/95	10
Vegetable seasonings (dried)	3	Unconditional	19/05/95	10
Vegetables (dried)	3	Unconditional	19/05/95	7
Yeast powder	3	Unconditional	19/05/95	7

Explanations for Codes: 1. Delay ripening/physiological growth. 2. Disinfestation. 3. Microbial control. 4. Quarantine treatment. 5. Shelf-life extension. 6. Sprouting inhibition. 7. Trichina/parasite control. 8. Sterile meals for hospital patients. 9. Sterilization. 10. Unstated.

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Mexico				
Beef (dehydrated)	3	Unconditional	07/04/95	10
Bulbs	2	Unconditional	07/04/95	0.2
Cereal grains	2	Unconditional	07/04/95	1
Cereal products	2	Unconditional	07/04/95	1
Chicken (dehydrated)	5	Unconditional	07/04/95	10
Chicken (fresh or frozen)	3	Unconditional	07/04/95	7
Chicken products (fresh or frozen)	5	Unconditional	07/04/95	3
Cocoa (dehydrated)	3	Unconditional	07/04/95	5
Condiments (dried)	3	Unconditional	07/04/95	10
Corn	2	Unconditional	07/04/95	1
Corn products	2	Unconditional	07/04/95	1
Egg (dehydrated)	3	Unconditional	07/04/95	5
Fish (fresh or frozen)	3	Unconditional	07/04/95	5
Fish (fresh or frozen)	5	Unconditional	07/04/95	3
Fish (fresh or frozen)	7	Unconditional	07/04/95	2
Food colours (natural, dehydrated)	3	Unconditional	07/04/95	10
Frog legs (fresh or frozen)	3	Unconditional	07/04/95	5
Frog legs (fresh or frozen)	5	Unconditional	07/04/95	3
Frog legs (fresh or frozen)	7	Unconditional	07/04/95	2
Fruit	1,4	Unconditional	07/04/95	1
Fruit	5	Unconditional	07/04/95	2.5
Fruit (dried)	2	Unconditional	07/04/95	1
Fruit (dried)	3	Unconditional	07/04/95	10
Garlic	6	Unconditional	07/04/95	0.2
Herbs	2	Unconditional	07/04/95	1
Herbs	3	Unconditional	07/04/95	10
Mango	1,4	Unconditional	07/04/95	1
Mango	5	Unconditional	07/04/95	2.5
Milk (dehydrated)	3	Unconditional	07/04/95	5
Mushrooms	1,4	Unconditional	07/04/95	1
Mushrooms	5	Unconditional	07/04/95	2.5
Onions	6	Unconditional	07/04/95	0.2
Papaya	1,4	Unconditional	07/04/95	1
Papaya	5	Unconditional	07/04/95	2.5
Pork	7	Unconditional	07/04/95	1
Potato	6	Unconditional	07/04/95	0.2
Rice	2	Unconditional	07/04/95	1
Rice products	2	Unconditional	07/04/95	1
Roots and tubers	6	Unconditional	07/04/95	0.2
Soup stock (dehydrated)	3	Unconditional	07/04/95	10
Soybean	2	Unconditional	07/04/95	1
Soybean products	2	Unconditional	07/04/95	1
Tea, herbal	3	Unconditional	07/04/95	10
Vegetables	1,4	Unconditional	07/04/95	1
Vegetables	5	Unconditional	07/04/95	2.5
Wheat	2	Unconditional	07/04/95	1
Wheat products	2	Unconditional	07/04/95	1
Netherlands				
Cereal flakes	2	Unconditional	01/08/92	1.5
Frog legs	3	Unconditional	01/08/92	7.5
Fruit (dried)	2	Unconditional	01/08/92	1.5
Gum arabic	3	Unconditional	01/08/92	15
Herbs	3	Unconditional	01/08/92	15
Legumes	2	Unconditional	01/08/92	1.5
Poultry	3	Unconditional	01/08/92	10.5
Shrimp	3	Unconditional	01/08/92	4.5
Spices	3	Unconditional	01/08/92	15
Sterile meals (frozen)	9	Unconditional	01/08/92	112.5
Vegetables (dried)	2	Unconditional	01/08/92	15
Norway				
Herbs	3	Unconditional	16/07/82	10
Spices	3	Unconditional	16/07/82	10
Vegetable seasonings (dried)	3	Unconditional	16/07/82	10
Pakistan				
Garlic	6	Unconditional	13/06/88	0.15
Onions	6	Unconditional	13/06/88	0.15
Potato	6	Unconditional	13/06/88	0.15
Spices	3	Unconditional	13/06/88	10
Philippines Note: The clearance for spices specifies a minimum dose of 6 kGy but no maximum.				
Garlic	6	Conditional	26/10/81	0.1
Onions	6	Conditional	26/10/81	0.1
Spices	3	Conditional	28/04/92	0
Poland				
Garlic	6	Unconditional	01/10/90	0.15
Mushrooms (dried)	3	Conditional	22/03/95	10
Onions	6	Unconditional	01/04/87	0.06
Spices	3	Unconditional	01/10/90	10
Vegetables (dried)	3	Conditional	22/03/95	10

Explanations for Codes: 1. Delay ripening/physiological growth. 2. Disinfestation. 3. Microbial control. 4. Quarantine treatment. 5. Shelf-life extension. 6. Sprouting inhibition. 7. Trichina/parasite control. 8. Sterile meals for hospital patients. 9. Sterilization. 10. Unstated.

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Russian Federation				
Beef, (raw, semi-prepared)	3	Conditional	11/07/64	8
Buckwheat mush (dried)	2	Unconditional	06/06/66	0.7
Food concentrates (dried)	2	Unconditional	06/06/66	0.7
Fruit	5	Conditional	11/07/64	4
Fruit (dried)	2	Unconditional	15/02/66	1
Grains	2	Unconditional	01/01/59	0.3
Gruel (dried)	2	Unconditional	06/06/66	0.7
Meat products (prepared)	5	Conditional	01/02/67	8
Onions	6	Unconditional	17/07/73	0.06
Pork (raw, semi-prepared)	5	Conditional	11/07/64	8
Potato	6	Unconditional	17/07/73	0.3
Poultry	5	Conditional	04/07/66	6
Pudding (dried)	2	Unconditional	06/06/66	0.7
Rabbit (raw, semi-prepared)	5	Conditional	11/07/64	8
Rice	2	Unconditional	06/06/66	0.7
Vegetables	5	Conditional	11/07/64	4
South Africa				
Almonds (chopped)	3	Conditional	07/05/82	10
Avocado	2	Conditional	28/07/77	0.1
Baby food	3	Conditional	13/05/92	10
Bacon	3	Conditional	24/03/89	10
Beef (dehydrated)	3	Conditional	08/06/88	10
Beef bone extract	3	Conditional	18/01/91	20
Beef soup stock	3	Conditional	18/01/91	20
Bran (raw)	3	Conditional	14/10/85	10
Bread and cake crumbs	3	Conditional	20/11/87	10
Breakfast cereals	3	Conditional	30/04/82	8
Calcium gluconate monohydrate	3	Conditional	12/12/90	10
Casein	3	Conditional	23/09/92	10
Casings (hog)	3	Conditional	10/04/91	26
Cereal drink base	3	Conditional	16/10/90	10
Cereal muesli	3	Conditional	01/02/88	10
Chicken	3	Conditional	25/08/78	4
Coconut (dried)	3	Conditional	10/07/90	10
Cold meats	3	Conditional	19/09/89	10
Condiment paste	3	Conditional	09/05/85	10
Corn flour	3	Conditional	18/11/91	10
Egg (whole, broken)	3	Conditional	20/07/89	10
Egg albumin (powder)	3	Conditional	12/10/87	10
Egg powder	3	Conditional	20/11/87	10
Egg pulp (frozen)	3	Conditional	29/03/90	10
Fish	5	Conditional	09/03/87	2

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Frankfurters	3	Conditional	19/09/89	10
Fruit (dried)	3	Conditional	08/10/88	10
Fruit jams	3	Conditional	03/09/87	10
Fruit juices and concentrates	5	Conditional	11/08/82	3
Fruit pulp	3	Conditional	03/09/87	5
Garlic (dried)	3	Conditional	02/07/91	10
Garlic paste	3	Conditional	24/05/89	10
Gelatine	3	Conditional	05/03/92	10
Ginger paste	3	Conditional	24/05/89	10
Green beans	2	Conditional	11/08/82	3
Health drink	3	Conditional	07/04/92	10
Herbs	2	Conditional	04/10/85	1
Honey	3	Conditional	26/10/92	13
Ingredients for health drink mixes	3	Conditional	07/04/92	10
Ingredients for marinades (powder)	3	Conditional	31/07/91	10
Mango	2	Conditional	25/08/78	4
Mango atchar	3	Conditional	14/05/87	10
Meat extract	3	Conditional	12/06/85	10
Milk shake powder	3	Conditional	02/05/88	10
Nuts	3	Conditional	22/04/91	10
Oats (rolled)	3	Conditional	10/04/89	10
Onion powder	3	Conditional	21/11/90	10
Onions	3	Conditional	19/03/91	10
Peanut	3	Conditional	16/10/90	10
Peanut butter	3	Conditional	12/12/93	10
Plum	2	Conditional	16/10/90	10
Pork crackling	3	Conditional	07/07/88	10
Potato	6	Conditional	06/02/87	10
Potato chips (raw, cooked)	3	Conditional	28/08/91	10
Poultry	3	Conditional	12/12/89	10
Rice (brown)	3	Conditional	20/09/91	10
Sausages	3	Conditional	19/09/89	10
Sausages (dried)	3	Conditional	10/04/91	10
Seaweed (dried)	3	Conditional	25/05/88	10
Smoked salami	3	Conditional	18/04/91	10
Sorghum malt beer	5	Conditional	06/03/86	1
Soup powder	3	Conditional	12/10/89	10
Soya fibre	3	Conditional	23/01/86	10
Soya flour	3	Conditional	23/01/86	10
Soya powder	3	Conditional	25/04/88	10
Spices	3	Conditional	04/10/85	10
Starch	3	Conditional	14/01/91	10
Sterile meats	9	Conditional	01/10/89	50
Sugar solutions	3	Conditional	09/12/88	10
Sunflower kernels	2	Conditional	01/02/95	10
Supplements (dietary)	3	Conditional	29/01/88	10
Sweets	3	Conditional	25/08/88	10
Tea, black seed	2	Conditional	12/10/93	10
Tea, comfrey	2	Conditional	20/09/92	10
Tea, Rooibus	2	Conditional	16/01/85	10

Explanations for Codes: 1. Delay ripening/physiological growth. 2. Disinfestation. 3. Microbial control. 4. Quarantine treatment. 5. Shelf-life extension. 6. Sprouting inhibition. 7. Trichina/parasite control. 8. Sterile meals for hospital patients. 9. Sterilization. 10. Unstated.

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Texturized vegetable protein	3	Conditional	12/10/93	10
Tomato	5	Conditional	11/08/82	3
Vegetables (dried)	3	Conditional	11/11/83	10
Viennas	3	Conditional	19/09/89	10
Weight loss preparation	3	Conditional	11/10/88	10
Wors (dried)	3	Conditional	08/06/88	10
Yeast powder (brewers and torulite)	3	Conditional	25/10/90	10
Spain				
Onions	6	Unconditional	10/09/75	0.08
Potato	6	Unconditional	04/11/69	0.15
Syria				
Chicken	3	Unconditional	02/08/86	7
Cocoa beans	2	Unconditional	02/08/86	5
Condiments	3	Unconditional	02/08/86	10
Dates	2	Unconditional	02/08/86	1
Fish	5	Unconditional	02/08/86	2.2
Fish (dried)	2	Unconditional	02/08/86	1
Fish products	5	Unconditional	02/08/86	2.2
Legumes	2	Unconditional	02/08/86	1
Mango	2	Unconditional	02/08/86	1
Onions	6	Unconditional	02/08/86	0.15
Papaya	2	Unconditional	02/08/86	1
Potato	6	Unconditional	02/08/86	0.15
Rice	2	Unconditional	02/08/86	1
Spices	3	Unconditional	02/08/86	10
Strawberry	5	Unconditional	02/08/86	3
Wheat	2	Unconditional	02/08/86	1
Wheat products	2	Unconditional	02/08/96	1
Thailand				
Beans	2	Unconditional	04/12/86	1
Chicken	3,5	Unconditional	04/12/86	7
Cocoa beans	2	Unconditional	04/12/86	1
Cocoa beans	3	Unconditional	04/12/86	5
Fish	5	Unconditional	04/12/86	2
Fish (dried)	2	Unconditional	04/12/86	1
Fish products	5	Unconditional	04/12/86	2
Garlic	6	Unconditional	04/12/86	0.15
Indian jujubes (dried)	2	Unconditional	04/12/86	1
Mango	1,2	Unconditional	04/12/86	1
Moo yor (cooked sausage)	3,7	Unconditional	04/12/86	5
Nham (raw, fermented pork sausage)	3,7	Unconditional	04/12/86	4
Onions	6	Unconditional	04/12/86	0.15
Papaya	1,2	Unconditional	04/12/86	1
Potato	6	Unconditional	04/12/86	0.15
Rice	2	Unconditional	04/12/86	1
Sausages	3	Unconditional	04/12/86	5

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Shrimp (frozen)	3	Unconditional	04/12/86	5
Spices	2	Unconditional	04/12/86	1
Spices	3	Unconditional	04/12/86	10
Strawberry	5	Unconditional	04/12/86	3
Wheat	2	Unconditional	04/12/86	1
Wheat products	2	Unconditional	04/12/86	1
Ukraine				
Beef (raw, semi-prepared)	3	Conditional	11/07/64	8
Buckwheat mush (dried)	2	Unconditional	06/06/66	0.7
Food concentrates (dried)	2	Unconditional	06/06/66	0.7
Fruit	5	Conditional	11/07/64	4
Fruit (dried)	2	Unconditional	15/02/66	1
Grains	2	Unconditional	01/01/59	0.3
Gruel (dried)	2	Unconditional	06/06/66	0.7
Meat products (prepared)	5	Conditional	01/02/67	8
Onions	6	Unconditional	17/07/73	0.06
Pork (raw, semi-prepared)	5	Conditional	11/07/64	8
Potato	6	Unconditional	17/07/73	0.3
Poultry	5	Conditional	04/07/66	6
Pudding (dried)	2	Unconditional	06/06/66	0.7
Rabbit, (raw, semi-prepared)	5	Conditional	11/07/64	8
Rice	2	Unconditional	06/06/66	0.7
Vegetables	5	Conditional	11/07/64	4
United Kingdom Note: In the UK Clearances, 'fruit' includes mushrooms, tomatoes and rhubarb; 'vegetables' include pulses; 'bulbs and tubers' means potatoes, yam, onions, shallots and garlic; 'fish and shellfish' includes eels, crustaceans and molluscs.				
Bulbs	6	Unconditional	01/01/91	0.2
Cereal grains	2	Unconditional	01/01/91	1
Condiments	3	Unconditional	01/01/91	10
Fish	5	Unconditional	01/01/91	3
Fruit	2	Unconditional	01/01/91	2
Poultry	3	Unconditional	01/01/91	7
Shellfish	3	Unconditional	01/01/91	3
Spices	3	Unconditional	01/01/91	10
Sterile meals	9	Conditional	01/01/91	100
Vegetable seasonings (dried)	3	Unconditional	01/01/91	10
Vegetables	2	Unconditional	01/01/91	1
Uruguay				
Potato	6	Unconditional	23/06/70	0.15
USA				
Enzymes (dehydrated)	3	Unconditional	18/04/86	10
Fruit	2	Unconditional	18/04/86	1
Herbs	3	Unconditional	18/04/86	30

Explanations for Codes: 1. Delay ripening/physiological growth. 2. Disinfestation. 3. Microbial control. 4. Quarantine treatment. 5. Shelf-life extension. 6. Sprouting inhibition. 7. Trichina/parasite control. 8. Sterile meals for hospital patients. 9. Sterilization. 10. Unstated.

Table 10: *continued*

Country Item name	Code	Type of clearance	Date	Max dose (kGy)
Pork	7	Unconditional	22/07/85	1
Poultry (fresh or frozen)	3	Unconditional	21/09/92	3
Poultry meat (mechanically separated	3	Unconditional	21/09/92	3
Spices	3	Unconditional	18/04/86	30
Vegetable seasonings (dried)	3	Unconditional	18/04/86	30
Vegetables (fresh)	2	Unconditional	18/04/86	1
Vietnam				
Fish (dried)	2	Conditional	03/11/89	1
Garlic	6	Conditional	03/11/89	0.1
Green beans	2	Conditional	03/11/89	1
Maize	2	Conditional	03/11/89	1
Onions	6	Conditional	03/11/89	0.1
Paprika powder	2	Conditional	03/11/89	1
Potato	6	Conditional	03/11/89	0.15
Former Yugoslavia				
Cereal grains	2	Unconditional	17/12/84	10
Egg powder	3	Unconditional	17/12/84	10
Fruit (dried)	2	Unconditional	17/12/84	10
Garlic	6	Unconditional	17/12/84	10
Legumes	2	Unconditional	17/12/84	10
Mushrooms (dried)	2	Unconditional	17/12/84	10
Onions	6	Unconditional	17/12/84	10
Potato	6	Unconditional	17/12/84	10
Poultry	3	Unconditional	17/12/84	10
Spices	3	Unconditional	17/12/84	10
Tea extract	3	Unconditional	17/12/84	10
Tea, herbal	3	Unconditional	17/12/84	10
Vegetables (dried)	2	Unconditional	17/12/84	10

Explanations for Codes: 1. Delay ripening/physiological growth. 2. Disinfestation. 3. Microbial control. 4. Quarantine treatment. 5. Shelf-life extension. 6. Sprouting inhibition. 7. Trichina/parasite control. 8. Sterile meals for hospital patients. 9. Sterilization. 10. Unstated.

Horse bean, broad bean, field bean (*Vicia faba*)
Bengal gram, chickpea (*Cicer arietinum*)
Lablab (*Dolichos lablab*)
Peas (*Pisum sativum*)
Rajmah, Tortola bean, French, kidney, haricot bean (*Phaseolus vulgaris*)
Red gram, pigeon pea (*Cajanus cajan*)
Black gram (*Phaseolus mungo, Vigna mungo*)
Cowpea (*Vigna unguiculata, V. sinensis*)

The oilseeds, groundnut (*Arachis hypogaea*) and soya bean (*Glycine max*), are also classed as legumes.

For insect disinfestation, a dose up to a maximum of 1 kGy is recommended. For improvement in quality, the dose should be in excess of 2 kGy.

Insect disinfestation

Stored legumes are susceptible to high losses due to *insect* attack. Bruchid beetles (*Callosobruchus* spp.) are major pests infesting pulses. A radiation dose of 0.3 kGy prevents adult *insect* emergence; a dose of 0.5 kGy is recommended for disinfestation of pulses (Bhuiya *et al.*, 1991). *Insect* pests associated with oilseeds include *Tribolium* spp., *Dermestes maculatus*, *Sitotroga cerealella* and *Oryzaephilus surinamensis*. These insects are more radiation resistant than *Callosobruchus* spp. and may require higher doses in the range 0.5–1 kGy for effective disinfestation (Bhuiya *et al.*, 1991).

Insect resistant *packaging* of pulses is essential. It has been recommended that PVC bags and polyethylene-lined jute bags are used for *packaging* pulses and oilseeds to protect against bruchid beetles, grain beetles and moths (Bhuiya *et al.*, 1991). A polyester-polyethylene laminate was found to be effective *insect* proof *packaging* for pulses (El Kady and Hekal, 1991).

Legal clearance for irradiation of pulses is given in a number of Asian and South American countries, China, Israel, and The Netherlands (see Table 10). Market trials of irradiated pulses have taken place in Bangladesh (see Table 11, page 98) and commercial use is planned (Hossain, 1994).

Quality improvement

Irradiation can improve the quality of legumes. Radiation doses in the range 2.5–10 kGy caused a reduction in cooking time (Rao and Vakil, 1985; Naji *et al.*, 1986). The percentage reduction depended on legume variety. Reduction in cooking time increased with increasing radiation dose. Improvements in *texture* were accompanied by a slight discolouration of the product. No *off-flavours* were produced below a dose of approximately 5 kGy. Softening of beans is attributed to radiation-induced depolymerization of *starch*, *pectin* and *cellulose*.

Irradiation has been shown to improve the digestibility of legumes by reducing the flatulence-causing oligosaccharides, raffinose, stachyose and verbascose (Hasegawa and Moy, 1973; Sreenivasan, 1974). Accelerated degradation of oligosaccharides to monosaccharides such as glucose and fructose means that legumes are more easily digested by the gastrointestinal tract.

The potential of irradiation to reduce antinutritional factors in legumes has been considered. Doses up to 10 kGy appeared to have no effect on trypsin inhibitor or lipoxygenase activities in soya bean (Kovacs *et al.*, 1991). A combination of soaking at 50°C, and a dose of 1 kGy, was found to be an effective method of reducing the phytate content of soya beans (Sattar *et al.*, 1990).

Nutrition

In many countries, legumes are vital sources of *protein* and nutrients. The effects of irradiation on the nutritional value of legumes are, therefore, a serious concern.

Doses of 0.5–5 kGy caused losses of *thiamine* in mung bean and chickpea (Khattak and Klopfenstein, 1989a). Losses were of the order of 16% at 5 kGy, and

3% at 1 kGy. *Niacin* and *riboflavin* were relatively stable. Losses of sulphur-containing amino acids, methionine and cysteine were reported at 5 kGy (Khattak and Klopfenstein, 1989b).

There are reports of an improvement in the nutritional value of irradiated pulses (Diehl, 1991). The availability of *riboflavin* was considerably improved in beans, treated with a dose of 1 kGy, with little effect on *thiamine* and *pyridoxine* content. The percent available lysine was higher in irradiated pulses (Khattak and Klopfenstein, 1989b).

See also Insect disinfestation; Legislation; Market trials; Nutrition.

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Lemon (*Citrus limon*)

The use of irradiation as a method of *insect disinfestation* for lemons may be limited by the low radiation resistance of the *fruit*. Lemons are sensitive to radiation doses even as low as 0.5 kGy (Akamine and Moy, 1983). Injury in the form of peel damage appears to be the limiting factor.

A range of effects as observed in 'Lisbon' lemons treated with radiation doses of up to 1 kGy, and stored at 15°C for 6 weeks (Jessup *et al.*, 1992). Acceleration of yellow *colour* formation in green lemons, flesh and peel softening and discolouration, and button senescence were evident. Peel damage occurred at doses as low as 0.075 kGy in green lemons. However, the quality of 'Eureka' lemons irradiated at 0.3–1 kGy, and then stored at 7°C, was well preserved for 6–7 weeks (Moy and Nagai, 1985).

See also Citrus fruits; Legislation.

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Lentil *see* Legume.

Lepidoptera *see* Insects.

Lettuce (*Lactuca sativa*)

Doses of 0.25–2 kGy caused radiation injury in the form of spotting, browning and pink rib in lettuce (Bramlage and Lipton, 1965). Although a dose of 0.5 kGy reduced decay, this resulted in an unacceptable level of injury.

Reference

Bramlage, W.J. and Lipton, W.J. (1965) *Gamma Radiation of Vegetables to Extend Market Life*, Market Research Report No. 703, Agricultural Research Service, US Dept of Agriculture, Washington, DC, pp. 11–12.

Lime (*Citrus aurantifolia*)

The use of low radiation doses to increase the storage life of limes has been investigated. Irradiated limes decayed at a slower rate when treated with a dose of 0.3 kGy (Mathur, 1963). Degreening was inhibited in the irradiated *fruit*. At doses of 0.5–1 kGy, accelerated deterioration of the *fruit* was observed (Avadhani and Lian, 1985).

A *combination treatment* of mild heat (45°C for 5 minutes) and a dose of 0.5 kGy provided a *mould*-free period of 32 days for lime fruit (Nyambati and Langerak, 1982). Deterioration occurred in untreated *fruit* after 1 day, and after 8 days with 0.5 kGy alone. A combination of mild heat, 0.5% potassium bisulphate, and 0.25 kGy gave a *mould*-free period of 12 days. A slight decrease in firmness was evident.

See also Citrus fruit; Juice.

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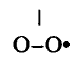
Lipid breakdown *see* Volatiles.

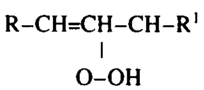
Lipids

The irradiation of unsaturated fatty acids in foods predominantly results in the formation of alpha and beta unsaturated carbon compounds (Nawar, 1983). Further reaction, and the addition of *oxygen*, leads to the formation of a *hydroperoxyl radical*:



$$\mathrm{R{-}CH{=}CH{-}\underset{\substack{|\\ O{-}O\bullet}}{Ch}{-}R^{1}}$$

then formation of a hydroperoxide:



$$\mathrm{R{-}CH{=}CH{-}\underset{\substack{|\\ O{-}OH}}{CH}{-}R^{1}}$$

The hydroperoxides are generally unstable in foods and breakdown to form mainly carbonyl compounds, many of which have low odour thresholds, and contribute to the rancid notes often detected when fat-rich (and particularly unsaturated fat-rich) foods are irradiated (Hammer and Wills, 1979; Wills, 1981). For example, irradiation of whole egg and egg yolk powder resulted in the generation of lipid hydroperoxides (Katusin-Razem *et al.*, 1992). In the absence of air, their formation was limited by available *oxygen*. Interestingly, destruction of carotenoids was strongly correlated with hydroperoxide formation.

Irradiation in the presence of *oxygen* leads to accelerated autoxidation (Diehl, 1990), but the end products are similar to those found following long storage of unirradiated lipids (Urbain, 1986).

See also Dairy products; Eggs; Free radical; Volatiles.

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Listeria

General

Listeria are small Gram-positive non-sporing rod-shaped *bacteria*. Although growing most rapidly at temperatures between 30 and 37°C, some strains are capable of growth at temperatures as low as 0°C and so are true psychrotrophs. They are widespread environmental contaminants and therefore gain access to many non-sterilized and non-pasteurized foods. Along with their salt-tolerance, their ability to grow at low temperatures makes them of particular concern in a wide range of chill-stored foods, although a relatively small proportion of cases have actually been shown to have a food-borne origin.

Of the five species currently recognized, three (*L. innocua, L. welshsimeri* and *L. seeligeri*) are regarded as non-pathogenic. *L. ivanovii* may occasionally cause disease, but *L. monocytogenes* includes the strains most often pathogenic for humans. Three of the known serotypes (1a, 1b and 4b) cause more than 90% of infections.

Types 1a and 1b are most often associated with neonatal infections and type 4b is most often associated with infections after birth.

Radiation resistance

L. monocytogenes is more radiation-resistant than the common Gram-negative spoilage micro-organisms of fresh proteinaceous foods, but has similar sensitivity to that of the Gram-negative enteropathogens including strains of *Escherichia coli* and *Salmonella*. In model systems and in *poultry*, *D-values* of more than 0.7 kGy have been reported (Huhtanen *et al.*, 1989). *D-values* of two serotype 1/2b outbreak strains, one serotype 1/2a and one serotype 1/2b strain of *Listeria monocytogenes*, γ-irradiated at 12°C, in minced uncooked chicken meat or in phosphate-buffered saline, in plastic test tubes, were determined. *D-values* of cells irradiated in chicken ranged from 0.48 to 0.54 kGy for cells recovered on non-selective medium (tryptone soya-yeast extract agar) and were generally slightly lower on selective agars (range 0.42–0.55 kGy). Values for cells irradiated in buffered saline were 0.39–0.47 kGy and 0.38–0.49 kGy respectively (Patterson, 1989).

Irradiation at 2.5 kGy greatly reduced the naturally occurring incidence of *L. monocytogenes* on raw chicken (Lewis and Corry, 1991). The only other species of *Listeria*, which was found on 44% of unirradiated chickens, but not on irradiated ones, was *L. innocua*. Patterson, Damaglou and Buick (1993) irradiated and chill-stored raw and cooked chilled *poultry* meat and concluded that even should low numbers of *L. monocytogenes* survive a low radiation dose, they would not be a problem during the shelf-life of a product because of their slow recovery rates.

Listeria monocytogenes has been implicated in several outbreaks traced to contamination and multiplication of the organism in cheese and other *dairy products*. Whilst *poultry* and poultry products suffer little organoleptic damage from low-dose irradiation, *dairy products* are generally regarded as unsuitable candidates for irradiation because off-odours and *flavours* are noticeable after even very low doses (Jones and Jelen, 1988). However, it has been reported that Camembert cheese made from unpasteurized milk can be successfully irradiated to reduce the incidence of contamination by *Listeria* provided that storage temperature and conditions of *ripening* are carefully controlled (Langley, 1988).

See also Dairy products.

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Liver fluke *see* Parasites.

Longan (*Euphoria longana*)

The longan is a tropical *fruit* that is a close relative of the *lychee* and *rambutan*. It grows in south east Asia and is exported mainly from India. Quarantine treatment of the longan against the oriental fruit fly using irradiation has been considered (Komson *et al.*, 1992). Doses of the order of 2 kGy reduced *fruit* decay during storage, with little effect on organoleptic quality (Thomas, 1988).

See also Insect disinfestation.

References

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Lychee (*Litchi chinensis*)

Post-harvest storage of lychees is limited by decay and desiccation. Irradiation of lychees to improve shelf-life, using doses in excess of 0.25 kGy, resulted in unacceptable surface darkening (Thomas, 1988). Pericarp browning occurred at doses above 0.6 kGy (Jessup *et al.*, 1992). At lower doses, 0.075–0.3 kGy, appropriate for fruit fly disinfestation, there were no adverse effects on *fruit* quality (McLaughlan *et al.*, 1992). Disease caused by the *mould Colletotrichum* spp. was reduced, but other unidentified species increased. Lychees treated with a combination of PVC wrapping plus irradiation, and stored at 4°C, showed no adverse effects on *fruit* quality and no *mould* development.

Irradiation of lychees for the purposes of disinfestation is given legal clearance in China (see Table 10, page 86).

See also Insect disinfestation.

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M

Maize *see* Cereals; Sweetcorn.

Mango (*Mangifera indica*)

For disinfestation (fruit fly, mango seed weevil) and for extension of storage life by delaying ripening and controlling fungal disease, the recommended dose is 0.25–0.75 kGy (in combination with a hot water dip).

Insect disinfestation

Irradiation is an alternative to chemical fumigants as a method of *insect disinfestation*. Mango fruit may be infested by fruit flies, such as the Oriental fruit fly and the Queensland fruit fly. The mango seed weevil is another major *insect* pest. Doses of 0.1–0.25 kGy gave satisfactory control of fruit flies and had no adverse effects on *fruit* quality (Heather and Corcoran, 1992; Manoto *et al.*, 1992). A minimum dose of 0.3 kGy is required to control the mango seed weevil; this dose is near the threshold for damage of certain mango varieties. Irradiation is considered to be the only disinfestation treatment capable of achieving quarantine security against the mango seed weevil (Heather, 1992).

Guidelines

A Code of Good Irradiation Practice for Insect Disinfestation of Fresh Bananas, Mangoes and Papayas, ICGFI Document No. 1, 1991, is published by the International Atomic Energy Agency.

Shelf-life extension

Irradiation has been used to extend the shelf-life of mangos by a delaying *fruit ripening* and by controlling fungal disease (reviewed by Thomas, 1986).

Treatment of fully matured *fruits* in the hard green pre-climacteric state is recommended. Irradiation of immature mangoes may result in increased shrivelling and uneven *ripening*. The optimum dose for delaying *ripening*, and the maximum dose that can be tolerated by *fruits*, depends on *fruit* variety (Thomas, 1986). Doses of the order of 0.25 kGy appear to be optimal for Indian and Pakistani varieties of mango; varieties grown in Hawaii and Puerto Rico may withstand higher doses up to 1 kGy. Radiation doses above the threshold for tolerance result in skin spotting and blackening of *fruit*; with deterioration of *flavour* and aroma.

The fungal pathogen *Colletotrichum gleosporoides*, which causes anthracnose, and *Diplodia natalensis*, which causes stem end rot, are responsible for decay in mangoes. Doses in the range 0.75–1.5 kGy are needed to control these *moulds* but result in unacceptable injury. A *combination treatment* of a hot water dip (50°C, 10 minutes) and irradiation (0.25–0.75 kGy) has been found to reduce post-harvest spoilage by these fungal diseases (Thomas, 1986). A treatment of hot benomyl or hot water (52°C for 5 minutes) with doses of 0.3–0.6 kGy was optimal for 'Kensington Pride' mangoes (Jessup *et al.*, 1988). Total soluble solids, sensory quality and *ascorbic acid* content of mango 'Keitt' variety were unaffected by radiation doses up to 0.95 kGy (Lacroix *et al.*, 1990).

The combination of hot water dip treatment followed by irradiation is the treatment of choice for mangoes. This treatment controls *insect* infestation and increases storage life by delaying *ripening* and reducing fungal spoilage.

Potential application

Successful small-scale and semi-commercial transportation studies of irradiated mangoes have been reported (Thomas, 1986). Favourable consumer reaction to irradiated mangoes was demonstrated in marketing trials in the United States (Giddings, 1986) (see Table 11, page 98).

Legal clearance for the irradiation of mangoes is given in a number of countries, including Bangladesh, China, South Africa, Syria, Thailand and USA (see Table 10, page 86). The *economic* feasibility of irradiation as a quarantine treatment for Mexican mangoes has been evaluated (Bustos *et al.*, 1993).

See also Atchar; Insect disinfestation; Legislation; Moulds; Ripening and senescence.

References

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Table 11 Market trials of irradiated food by country (after Anon, 1990 and Loaharanu, 1993, with permission).

Country	Irradiatead food items	Date of testing	Results
Argentina	Onion, garlic, garlic powder	1985–1988	Consumers positive to irradiated foods; preference for irradiated onions
Bangladesh	Potato, onion, dried fish, pulses	1984–1988	Consumers preferred irradiated foods
China P.R.	Spirit from sweet potato, sausage, apple, potato, hot pepper and products, orange and pear	1984–1990	Consumers positive to irradiated products
Cuba	Potato, onion, garlic	1988	Consumers positive to irradiated products
France	Strawberry	1987–1988	Consumers preferred irradiated strawberries despite the higher price
Germany	Chicken, spices	1985–1987	Consumers positive to irradiated products
Indonesia	Dried fish	1986–1988	Consumers positive to irradiated products
Pakistan	Potato, onion	1984–1987	Consumers positive to irradiated products
Phillipines	Onion, garlic	1984–1987	Consumers positive to irradiated products
Poland	Onion, potato	1986–1988	Preference for irradiated foods
Thailand	Nham (fermented pork sausage), onion, garlic	1986–1988	Preference for irradiated nham in ratio 10:1; consumers positive to irradiated onions and garlic
USA	Mango, papaya, apple	1986–1988	Consumers preferred irradiated mangoes and apples; irradiated papayas sold in ratio 11:1 over untreated fruit
Former Yugoslavia	Herbal extracts	1984–1985	Consumers positive to irradiated products

Thomas, P. (1986) Radiation preservation of foods of plant origin. Part III. Tropical fruits: bananas, mangoes and papayas, *Critical Reviews in Food Science and Nutrition*, **23**(2), 147–205.

Mango seed weevil (***Sternochaetus mangiferae***) *see* Insects.

Mangosteen (***Garcinia mangostana***)

The mangosteen is a tropical *fruit* grown extensively in Indonesia and Malaysia. The use of irradiation as a quarantine treatment for the mangosteen against fruit flies has been investigated (Komson *et al.*, 1992). A dose of 0.15 kGy was found to be an effective treatment that did not affect *fruit* quality. Higher doses delayed *colour* development and increased peel hardness.

See also Fruit and vegetables.

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Market trials

Market trials of irradiated food, which took place between 1984 and 1990, are summarized in Table 11.

More recent market trials of irradiated food, in countries including the USA, Pakistan and China, are reviewed by Bruhn (1995). In 1992, irradiated *strawberries* were sold in Florida and Chicago (Marcotte, 1992). Irradiated products sold at the same rate as the untreated products when priced the same. In addition, market trials of small volumes of irradiated *oranges*, *grapefruits*, *onions*, *tomatoes* and *mushrooms* took place (Pszczola, 1992). Analysis of sales of irradiated produce, cost comparisons of irradiated and non-irradiated products, information for consumers and market strategy are discussed by Corrigan (1993). In 1993, irradiated *poultry* was sold in selected supermarkets in the United States (Pszczola, 1993). Irradiated *poultry* sold out at a similar price to the non-irradiated products.

The results of market trials indicate that consumers will accept irradiated food if they are given science-based information, and if the irradiated product offers clear advantages (Bruhn, 1993). Certain irradiated food products are in small-scale commercial use (see Table 5, page 32).

See also Consumer attitudes; Economics.

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Meat

For control of meat-borne parasites, e.g. *Trichinella spiralis* in pork, the recommended dose is 0.3–1 kGy. To increase shelf-life and reduce the numbers of pathogenic bacteria in fresh meat, the recommended dose is 1–3 kGy.

Parasite control

High *economic* losses are caused by food-borne *parasites* (Roberts and Murrell, 1993). Irradiation of pork and beef is a potential method of reducing meat-borne parasitic disease (see Table 17, page 121) and associated costs.

Trichinae (*Trichinella spiralis*) are parasitic nematodes that form cysts in pig muscle. If the cysts are ingested in raw or undercooked pork, this results in a disease called trichinosis. A minimum effective dose of 0.3 kGy has been established for the control of *Trichinella* (IAEA, 1993). In 1985, legal clearance was granted, in the USA, for the irradiation of pork, at a minimum absorbed dose of 0.3 kGy but not exceeding 1 kGy (Engel *et al.*, 1988).

Toxoplasma gondii is an intracellular protozoan *parasite*, which is responsible for toxoplasmosis, an important cause of congenital malformations. Pork and pork products are considered to be potential sources of toxoplasmosis (Murrell and Dubey, 1993). Infectivity of *Toxoplasma gondii* is destroyed at 0.5 kGy, but a minimum effective dose of 0.7 kGy is recommended in order to account for strain variation (IAEA, 1993).

Taeniasis/Cysticercosis is caused by the beef tapeworm, *Taenia saginata*, or the pork tapeworm, *Taenia solium*. These diseases are found worldwide, in areas of poverty and poor hygiene, and can lead to serious neurological problems. A minimum effective dose for the control of these organisms has not been established but doses below 1 kGy may be effective in man (IAEA, 1993).

Spoilage bacteria

The group of *bacteria* responsible for spoilage of red meats at low temperatures belong to the *Pseudomonas-Achromobacter* (*Moraxella-Acinetobacter*) association (Ingram, 1975). In irradiated meat, there is a shift from *Pseudomonas* species, which are relatively radiation sensitive, to the more radiation resistant Achromobacter. A shift from Gram-negative to Gram-positive elements is also observed (Lefebvre *et al.*, 1992; Tiwari and Maxcy, 1971). In irradiated vacuum-packaged or modified-atmosphere packaged (MAP) meats, lactic acid *bacteria* and *yeasts* comprise the surviving microflora (Niemand *et al.*, 1981). Spoilage odours that develop on irradiated meat will reflect the final microflora (Dempster, 1985).

Low radiation dose treatment of meat gives a substantial increase in shelf-life because *Pseudomonas* species are very radiation sensitive.

Pathogenic bacteria

Radiation doses of 1–2 kGy result in a reduction in pathogens, such as *Salmonella*, *Yersinia enterocolitica*, *Campylobacter jejuni*, *Escherichia coli*, *Staphylococcus aureus*, *Listeria* and *Aeromonas* (Tarkowski *et al.*, 1984a, b; Radomyski, 1993). Irradiation could be used to prevent infection by the highly enteropathogenic *E. coli* 0157:H7, which has already caused deaths and many illnesses from the consumption of raw or undercooked meat (Karr and Marsden, 1994).

Spore-forming pathogens such as *Clostridium botulinum* are rather resistant to radiation. Since a high radiation dose, which would cause unacceptable changes in meat, would be required to eliminate these pathogens, strict control over meat storage conditions, by good manufacturing practice, is required. The use of low temperature storage of 2–4°C is essential.

At abuse temperatures, growth of pathogenic *bacteria* in irradiated meat may occur. Low-temperature storage is necessary for the safety of the product. There is a risk of *toxin* production by *Clostridium botulinum* in vacuum packed and MAP meat (Lambert *et al.*, 1991; 1992; Lebepe *et al.*, 1990). Concern about *toxin* production occurring before meat spoilage may be valid, if radiation doses are in excess of 3 kGy. In temperature abuse conditions, *C. botulinum* may be able to compete more successfully when high radiation doses have reduced the natural microflora (Grant and Patterson, 1991b).

Guidelines

- A Code of Good Irradiation Practice for Prepackaged Meat and Poultry Products (to control pathogens and/or extend shelf-life), ICGFI Document No. 4 International Atomic Energy Agency, Vienna (1991).
- F1356 – Guide for the Irradiation of Fresh and Frozen Red Meats and Poultry (to control pathogens). Annual Year Book of the American Society for Testing and Materials (ASTM) Standards, 15.07 (1993).

Treatment

Irradiation of meat to extend shelf-life and reduce numbers of pathogenic *bacteria* must be applied to meat of good hygienic quality (Grant and Patterson, 1991b). Relevant *codes of practice* for fresh or frozen meats, and good manufacturing practice, should be adhered to in order to maintain the quality of meat for irradiation treatment. A temperature below 4°C, for chilled meats, and −18°C or below, for frozen meat, should be maintained. Irradiation should take place as soon as possible after slaughter. For frozen products, the pre-irradiation storage period should be kept to a minimum.

The radiation dose required for shelf-life extension and reduction of pathogenic *bacteria* of fresh red meats stored at refrigeration temperatures is in the range 1–2.5 kGy. Choice of dose will depend on type and numbers of *micro-organisms* present, *temperature*, *packaging*, gaseous environment, food pH, *water activity* and food *additives*, e.g. *nitrite*, sodium chloride, phosphates (Thayer *et al.*, 1986). A twofold increase in shelf-life may be achieved with a dose of the order of 2 kGy.

Flexible films or laminates chosen for *packaging* irradiated meat must act primarily as a barrier to penetration by *micro-organisms*. Gas and water vapour properties will affect the final product quality. *Packaging* of carcases prior to irradiation is a possibility (MacFarlane *et al.*, 1983), although pre-irradiation *packaging* of meats cuts is more likely.

Vacuum packaging

Exclusion of *oxygen* prevents fat oxidation and the development of rancidity in irradiated meats; in addition meat *colour* is protected. Vacuum packaging has been recommended for the preservation of the sensory properties of irradiated meat, although there have concerns about microbiological safety (Lebepe *et al.*, 1990; Grant and Patterson, 1991b). Irradiation of vacuum-packed pork is not permitted in the United States (Anon, 1986).

A system for preserving the quality of irradiated meat has been suggested. It is particularly recommended for beef, which is highly pigmented; it may not be necessary for pork and veal (Urbain, 1986):

- Addition of polyphosphate to meat to control drip and stabilize meat *colour.*
- Double packaging, i.e. the meat cut is wrapped in *oxygen* permeable film, then placed in a bulk container that is evacuated; in this way the anaerobic environment protects meat *colour* but prevents *lipid* oxidation.
- Irradiation at 1–2 kGy between 0–10°C; storage and transport not exceeding 5°C.
- Retail cuts are removed from bulk packaging for about 3-days display. Access of *oxygen* to the product is provided in order to obtain the normal red *colour* needed for marketing.

Combination processing

The benefits of a combination of irradiation of meat with mild heat treatment, vacuum packaging or MAP have been highlighted by Radomyski *et al.* (1993) and Patterson (1993). *Combination treatments* involve a lower dose of *ionizing radiation*, thus preserving the quality of the product.

The use of irradiation in combination with modified atmosphere packaging (MAP) has been recommended for pork (Grant and Patterson, 1991a; Lambert *et al.*, 1992). Doses as low as 0.5 kGy, in an atmosphere of 10% O_2:90% N_2, resulted in a shelf-life of 6 days at 5°C; meat treated at 1 kGy in an atmosphere with 0% oxygen gave a shelf-life of 21 days (Lambert *et al.*, 1992). Grant and Patterson (1991a) recommended a dose of 1.75 kGy, in an atmosphere of 25% CO_2:75% N_2. At 5–7°C, the untreated meat shelf-life was 2–3 days, the MAP meat 8 days, and the irradiated MAP meat more than 12 days.

Low-dose irradiation combined with a reduction in *water activity*, or pH reduction, extended the shelf-life of vacuum-packed pork (Banati *et al.*, 1991).

Characteristics of fresh pork, lamb and beef

The sensory quality of irradiated meat depends on the animal species from which it is derived (see Table 12) (Sudarmadji and Urbain, 1972).

A radiation dose between 1–2 kGy results in sensory changes, principally in the form of irradiation odour, in vacuum-packed pork (Shay *et al.*, 1988). After storage, the odour dissipates and then organoleptic changes are considered to be acceptable. The presence of *oxygen* in the headspace of modified atmosphere packaged pork adversely affects the sensory qualities of the product. A modified atmosphere of 25% CO_2:75% N_2, combined with a radiation dose of 1.75 kGy, and storage at 4°C, is recommended for good microbiological and sensory qualities (Grant and Patterson, 1991a). Pork, in contrast to beef, does not appear to require the presence of oxygen in the packaging atmosphere, in order to maintain an acceptable *colour*.

Although there is evidence that lamb is relatively resistant to the formation of *off-flavours* (see Table 12), this may not be the case. Irradiation of vacuum-packed mutton backstraps at 4 kGy resulted in sensory changes (MacFarlane *et al.*, 1983). When lamb mince and chunks were packaged, and irradiated at 1 kGy and 2.5 kGy at 0–3°C, no irradiation odour was detected and acceptable scores for *colour* and *flavour* were achieved (Paul *et al.*, 1990). The threshold for change appears to be similar to that of pork.

Beef treated with doses of 1–2 kGy in anaerobic conditions has been extensively studied (MacFarlane *et al.*, 1983; Risvik, 1986; Wills *et al.*, 1987). Vacuum packing prevents fat oxidation and resultant rancidity *off-flavours*, and preserves meat colour (Urbain, 1986). There are a limited number of reports on the irradiation of aerobically packaged beef (e.g. Dempster, 1985; MacFarlane *et al.*, 1983; Shay *et al.*, 1988). Even using low doses of the order of 1 kGy or less, accelerated oxidation during storage may occur. Neither *flavour* nor *colour* changes were detected in raw minced beef treated with a radiation dose of 1 kGy (Tarkowski *et al.*, 1984b). For *sensory evaluation*, irradiated raw meat was mixed with a mayonnaise-type sauce consisting of salad oil, egg yolk, vinegar, salt and *spices* (filet-américain). This mixture may have disguised any radiation-induced changes.

Table 12 Threshold doses that give a detectable irradiation flavour in meats (Sudarmadji and Urbain, 1972). The raw meats were vacuum packed, irradiated at 5–10°C, then cooked in boiling water in plastic bags before taste panel evaluation. An irradiation flavour was detected at the threshold dose.

Food	**Threshold dose (kGy)**
Turkey	1.50
Pork	1.75
Beef	2.50
Chicken	2.50
Rabbit	3.50
Lamb	6.25
Venison	6.25
Horse	6.50

Characteristics of processed meats

Vacuum-packed, sliced, processed meats, such as corned beef and luncheon meat, have a limited storage life due to microbial recontamination, which occurs during slicing and packing. In a study of corned beef (Shay *et al.*, 1988), a dose of 2 kGy was found to double the shelf-life at 5°C. Although changes in odour and *flavour* were apparent, they were considered to be acceptable.

In a range of sliced cooked meats (including sausage, smoked meat-products and ham), a substantial reduction in the spoilage microflora was achieved, using a radiation dose of 1 kGy, at refrigeration temperatures (or 2 kGy for frozen products) (Stekelenburg, 1990). Sensory quality was not seriously affected. These results applied to low-sodium meat products. In salted, cooked meat products at similar radiation doses, *off-flavours* were evident.

Irradiation of vacuum-packed bacon and ham has been reviewed (Dempster, 1985; Thayer *et al.*, 1986). Studies have been aimed at promoting microbiological safety and reducing the amount of *nitrite* required in cured meats. In meats treated with a nitrite-free curing system (cured meat pigment), and irradiated at 5 kGy and 10 kGy, no detrimental effect of irradiation on *colour* or oxidative stability of the meat samples was found (Shahidi *et al.*, 1991).

Irradiation of sausage batter, prior to addition of starter culture for fermentation, reduces the levels of pathogens in the final product (Dickson and Maxcy, 1985). The safety of Nham, a traditional fermented pork sausage of Thailand, is improved with irradiation treatment. The risks of *Salmonella* spp. and *Trichinella spiralis* are eliminated from the product using a radiation dose of 2 kGy (Prachasittaisak *et al.*, 1989).

Nutrition

The effect of irradiation on the B-vitamins in pork has been reported (Fox *et al.*, 1989). At a radiation dose of 7 kGy or less, there were no significant losses in *niacin, riboflavin, pyridoxine* or *cyanocobalamin. Thiamine* is relatively radiation sensitive. Losses of this vitamin in cooked pork chops, due to irradiation, at 0°C and at 0.3 and 1.0 kGy (the dose range proposed for trichina control), were 5.6 and 17.6%. It is calculated that the loss of *thiamine* in the American diet, due to irradiation of chops and roast pork, would be 1.5% at 1 kGy.

Potential application

Irradiation of pork for trichina control is permitted in the USA, but is not in commercial use. There is legal clearance for irradiation of meat products in countries including China, Cuba, Korea, Thailand, Mexico and South Africa (see Table 10, page 86). In Thailand, irradiated Nham (fermented pork sausage) is being sold at retail level (see Table 5, page 32), with a high degree of consumer acceptance.

The *economic* benefits of the irradiation of pork and beef have been evaluated by Morrison and Roberts (1985). In the United States, legal clearance for the irradiation of chilled meats may follow in the wake of recent legislation on *poultry*. Safety data needed to extend clearance of irradiation by the United States Department of Agriculture and the Food and Drug Administration for beef has been obtained (Anon, 1994).

See also Clostridium botulinum; Combination treatments; Commercial use; D-values; Legislation; Micro-organisms - relative resistance; Micro-organisms - safety; Nitrite reduction; Nutrition; Poultry; Sterilization.

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Mediterranean fruit fly *see* Insects.

Melon *(Cucumis melo)* (Cantaloupe, Honeydew)

The use of radiation, at doses above 1 kGy, to control of *mould* growth in melons has been investigated (Thomas, 1988). At these doses, softening of *fruit* may occur with injury in the form of sunken spots in the peel. The use of a hot water dip, in combination with irradiation, could improve the effectiveness of the treatment.

Radiation disinfestation of cantaloupe and honeydew melons as an alternative to fumigation by methyl bromide has been suggested (CAST, 1989).

See also Legislation.

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Melon fruit fly *see* Insects.

Micro-organisms – relative resistances

General

Radiation resistance varies widely between species of *bacteria*, *yeasts* and *moulds* (see Figure 10). Many of the common Gram-negative spoilage *bacteria* of high water activity, non-acid foods (e.g. *Pseudomonas*) and members of the Enterobacteriaceae including the pathogens (e.g. *Escherichia*, *Salmonella*, *Shigella*) are more

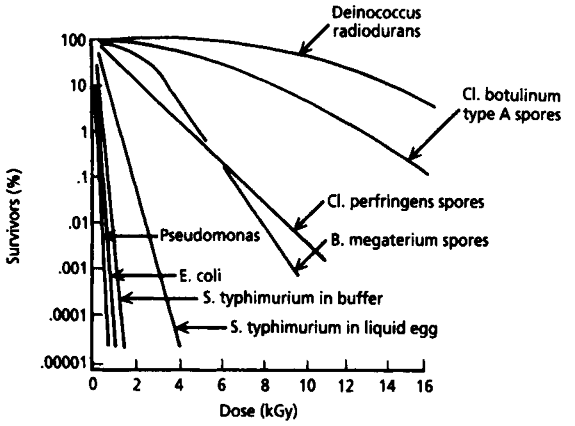

Figure 10 Variations in slope and shape of irradiation-survivor curves of different bacteria. The curves illustrate: the exponential inactivation kinetics with some organisms (e.g. *Pseudomonas, Escherichia coli, Salmonella typhimurium, Clostridium perfringens* spores); the marked influence of substrate that is sometimes seen (*S. typhimurium* in buffer and in liquid egg); the short (*Bacillus megaterium* spores) or long (*Clostridium botulinum* type A spores) 'shoulders' that are sometimes evident; the enormous 'shoulder' and resistance of *Deinococcus radiodurans*, which has an efficient DNA-repair system (from Goldblith, 1971).

radiation-sensitive than the vegetative forms of most Gram-positive bacteria (Welch and Maxcy, 1979), whilst the spores of *Bacillus* and *Clostridium* species are generally still more resistant (ICMSF, 1980).

Even more resistant are the cells of non-sporing organisms that have very efficient *DNA* repair systems, some being able to repair numerous double strand breaks, such as *Deinococcus radiodurans* (Anderson *et al.*, 1956) and related species (e.g. *D. radiopugnans, D. radiophilus, D. proteolyticus*) (Moseley, 1984; 1989).

Amongst the Gram-negative flora, typical of high water activity, non-acid foods undergoing spoilage, some members of the *Acinetobacter-Moraxella* group show exceptional radiation tolerance. They therefore tend to form the major component of the flora of such low-dose-irradiated foods (Hussain *et al.*, 1976). However, comprehensive studies of irradiated red *meat* and *poultry* showed that these micro-organisms did not cause unusual spoilage problems, and are not of public health significance (Karnop *et al.*, 1978; Snyder and Maxcy, 1979; Tiwari and Maxcy, 1972).

The vegetative *bacteria* of major food-poisoning concern are all much more radiation sensitive, so that low-dose irradiation will effectively eliminate them from contaminated food (e.g. *Yersinia enterocolitica, Vibrio parahaemolyticaus, Aeromonas hydrophila, Campylobacter* species, *Salmonella* species, enteropathogenic strains of *Escherichia coli, Shigella* species and *Listeria monocytogenes*).

Table 13 Microbial counts in irradiated frozen chicken (adapted from Mossel and Stegeman, 1985).

	Count ($\log_{10}$ per g) after irradiation at (kGy)				
Micro-organisms	*0*	*1*	*2*	*3*	*4*
Mesophiles	6.8	5.8	4.6	4.1	3.6
Psychrotrophs	5.8	5.9	4.0	<2.8	<1.8
Enterobacteriaceae	5.5	<2.8	1.0	0.4	–0.4
Lactobacillus	6.0	4.1	4.2	3.1	<2.8
Streptococcus (D)	5.1	3.7	3.9	3.2	<2.0
Staphylococcus aureus	4.6	2.2	<–0.5	<–0.5	<–0.5

Relative resistances in foods

Examples of the effectiveness of low dose irradiation on the major elements of the microbial flora of frozen *poultry* are given in Tables 13 and 14. The data in Table 13 show the substantial reduction in bacterial count that is obtained with doses as low as 3 or 4 kGy, with the *Enterobacteriaceae* being particularly sensitive. The 'percentage of total surviving flora' data, in Table 14, emphasize the selectivity of irradiation in reducing the Gram-negative organisms, disproportionately, in comparison to the Gram-positive ones and the *yeasts* (Mossel and Stegeman, 1985).

Modified atmosphere packing of foods may slightly enhance the radiation tolerance of some of the micro-organisms that they contain, but reduce the tolerance of others (Patterson, 1988). In general, although the

Table 14 Gram-negative to Gram-positive flora shift in irradiated frozen chicken (adapted from Mossel and Stegeman, 1985).

Micro-organisms	**Percentage of total flora after irradiation**			
	Mesophiles		**Psychrotrophs**	
	0 kGy	2 kGy	0 kGy	2 kGy
Gram-positive	(82)	(95)	(19)	(86)
Aerococcus	–	10	–	–
Micrococcus	28	39	–	83
Staphylococcus	10	–	–	–
Streptococcus (D)	3	43	–	–
Corynebacterium	19	3	19	3
Lactobacillus	22	–	–	–
Gram-negative	(16)	(0)	(81)	(0)
Acinetobacter	2	–	8	–
Xanthomonas	–	–	4	–
Pseudomonas	–	–	46	–
Kluyvera	–	–	5	–
Hafnia	10	–	7	–
Klebsiella	–	–	11	–
Escherichia coli	4	–	–	–
Yeasts	2	5	0	14

presence of *oxygen* in packaging gases may enhance the radiation sensitivity of some micro-organisms (Goldblith, 1971 and see Figure 11), it also adversely affects food *flavour*, e.g. of *pork* (Lambert *et al.*, 1992). Exceptions to sensitization by *oxygen* have been reported (Patterson, 1988 and see Table 18, page 131).

The spores of the spore-forming food-poisoning micro-organisms (*Clostridium botulinum*, *C. perfringens*, *Bacillus cereus* and possibly *B. subtilis* and *B. licheniformis*) have resistances well above those of the majority of vegetative bacteria, but below those of the *DNA*-repair-efficient species.

It is important to remember that the radiation resistances of micro-organisms depend not only on their intrinsic properties but also on the food substrate in which they are treated. However, in general, the reported *D-values* give good guidelines. For example, Grant and Patterson (1992) measured the D_{10} values of a range of food poisoning micro-organisms, irradiated in a complete chilled 'ready meal' containing roast *beef*, gravy, cauliflower, roast and mashed *potatoes*. *Bacillus cereus* (presumably in vegetative form) was the most sensitive with D_{10} values within the range 0.13 to 0.29 kGy, followed by *Staphylococcus aureus* (0.25 to 0.43 kGy), *Listeria monocytogenes* (0.30 to 0.65 kGy), *C. perfringens* (0.34 to 0.59 kGy) and *Salmonella typhimurium* (0.37 to 0.70 kGy). The pathogens all had lower *D-values* when irradiated in gravy than when irradiated in the other meal components.

Generally *moulds* have resistances similar to those of the less tolerant vegetative bacteria, whilst the resistance of some *yeasts* approaches that of the more tolerant vegetative bacteria.

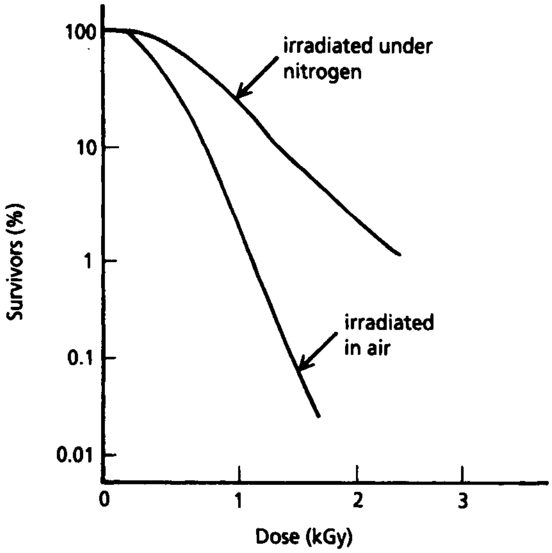

Figure 11 Enhanced sensitivity of *Enterococcus faecalis* in buffer, irradiated in air *versus* irradiation under nitrogen (from Goldblith, 1971).

Viruses are very radiation-resistant but, like all of the particularly radiation-resistant vegetative bacteria, are sensitive to heat.

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Micro-organisms – safety

There has been concern, and much discussion, about the possibility that the irradiation of foods may alter the ratios of micro-organisms present, or cause *mutations* in the survivors, in such ways as to introduce new microbiological hazards that were not present in the unirradiated foods. However, there is a general consensus now that, with proper control of raw material quality, processing, storage and distribution, such unexpected hazards will not occur (Diehl, 1987; Teufel, 1983; WHO, 1994).

For example, Farkas (1989) summarized the extensive previous reports of expert committees and the relevant scientific literature concerning the possibility that the microbiological safety of irradiated foods could be thus compromised, e.g. by:

- changes in food microflora, caused by non-sterilizing doses of radiation, resulting in a rise in the risk of occurrence or growth of pathogens, e.g. following inactivation of harmless competing flora;
- *mutations* or adaptive changes, enhancing the virulence of pathogens, or making pathogens less easily recognized, or even creating new pathogens;
- the development of radiation-resistant strains rendering the irradiation process itself ineffective.

He concluded that all the data reconfirmed that the microbial safety of irradiated food is fully comparable with that of foods preserved by other widely used preservation procedures. As with these other procedures, the gains in safety or keeping quality obtained must be safeguarded by proper controls in food irradiation facilities and by proper care of the product before and after processing.

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Milk *see* Dairy products.

Minerals and trace elements

Whilst certain minerals and trace elements are essential for health, irradiation of them at the energies employed in food processing brings about no changes. There is therefore no nutritional significance of irradiation of these *food components*.

See also Nutrition.

Mites *see* Insects; Insect disinfestation.

Modelling

Computer-based predictive mathematical models of microbial growth and survival have been developed in recent years (Baird-Parker and Kilsby, 1987; Gould, 1989). These mainly target food poisoning *micro-organisms* but, in future, will include increasing numbers of food spoilage *micro-organisms* as well. The models mainly describe the effects, on growth and survival, of parameters such as temperature of incubation, pH value, water activity, the presence of particular preservatives and different packaging atmospheres, as well as the effects of thermal processes on survivor levels, i.e. the kinetics of inactivation. A start has been made on the acquisition of similar data for irradiation processing, with the derivation of equations that describe the responses of *micro-organisms* to irradiation under different conditions. For example, *Staphylococcus aur-*

eus in chicken meat, irradiated over a range of doses and temperatures (Thayer and Boyd, 1992). Patterson *et al.* (1993) modelled the growth of *Listeria monocytogenes* surviving low irradiation doses in chicken mince as a function of temperature.

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Modified atmosphere packaging (MAP) *see* Combination treatments; Micro-organisms – relative resistances; Salmonella.

Moulds

General

The radiation resistance of some moulds has made their elimination from commodity foods by low doses of irradiation difficult. For instance, doses of 2 kGy were insufficient to control black mould rot of *apples*, caused by *Aspergillus niger*. However, if the *apples* were treated with low levels of fungicides (including Aureofungin, Benomyl, Captan) as well, a *synergistic* effect was seen that achieved effective control (Roy and Mukewar, 1973).

The radiation resistances of many moulds show substantial variability so that it is difficult to state realistic *D-values* for common spoilage types such as *Botrytis*, *Rhizopus* and *Pencillium*, etc.

Mycotoxins

The induction of *mutations* in *bacteria*, *viruses* and *yeasts*, during food irradiation under practical conditions, has been widely agreed not to constitute a problem. The much greater genetic variability of moulds has led to them being given special attention. For example, in laboratory studies it has been demonstrated that mould cultures derived from irradiated mould spores may show reduced *or* enhanced production of mycotoxins. This has also been demonstrated in laboratory studies in which large numbers of spores were irradiated in moist, sterile foods. These conditions are far away from those employed commercially and, under such commercial conditions, no evidence of enhanced mycotoxin formation has been found (WHO, 1981). Production of mycotoxin (tenazonic acid) by *Alternaria alternata* in tomato juice and tomato paste, for example, was influenced principally by water activity, temperature and irradiation dose, but decreasing the water activity and/or increasing the radiation dose clearly suppressed or eliminated mycotoxin formation (Aziz *et al.*, 1991).

O'Neill *et al.* (1993) confirmed the high radiation tolerance of mycotoxins once formed. Deoxynivalenol and 3-acetyl deoxynivalenol on dry grain were far too resistant to be affected by the low doses currently employed for *insect* or microbial decontamination.

There has been concern that low dose irradiation of dry commodity foods, such as *cereal grains*, may inactivate some of the potential spoilage *micro-organisms* that are always present, in such a way as to remove competitors and give an advantage to more radiation-resistant survivors. These might include mycotoxic moulds, such as certain strains of *Aspergillus flavus* and *Aspergillus parasiticus*, which are included amongst those in which laboratory studies (see above) have shown enhancement of mycotoxin production (Schindler *et al.*, 1980). In practice, however, these laboratory studies are not judged to indicate a realistic hazard. Proper storage of irradiated grain, and of other dry foods, under conditions of sufficiently low relative humidity, will ensure that the water activity is too low to allow growth of any surviving spores. If the humidity is allowed to rise, spoilage strains will begin to grow before the mycotoxin-formers, which are generally less tolerant of low water activity conditions.

See also Micro-organisms – relative resistances; Micro-organisms – safety; Mutations.

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MSM (mechanically separated poultry meat) *see* Chicken.

Mushroom *(Agaricus spp.)*

For inhibition of stem growth and cap opening, leading to increased shelf-life, the recommended dose is approximately 1 kGy.

Treatment

Irradiation can extend the shelf-life of *Agaricus* mushrooms by suppressing cap opening and stalk elongation (Thomas, 1988; Barkai-Golan, 1992). Darkening of the gills, cap and stalk, shrivelling and surface *mould* development are inhibited. The optimal dose requirement depends on factors including physiological age at harvest, variety, storage temperature, type of *packaging*, relative humidity and time elapsed between harvest and irradiation. A dose of 1 kGy, applied soon after picking at the closed button stage, gives the best results in terms of retardation of cap opening and stem elongation, without adversely affecting sensory quality. High radiation doses cause discolouration of the product.

Irradiation may be of limited use at storage temperatures near 0°C because low temperatures alone are very effective at slowing down growth and deterioration. Irradiation treatment could be advantageous for mushrooms stored in excess of 5°C (Thomas, 1988). An increase in shelf-life of 5 days may be achieved, using a dose of 1 kGy. A dose of 2 kGy extended the shelf-life of *Agaricus bisporus* mushrooms by 3–4 days at 15°C (Beaulieu *et al.*, 1991). A radiation dose of 0.5 kGy improved the sensory quality of fresh *Volvariella volvacea* mushrooms (Nayga-Mercado and Alabastro, 1989). An increase in shelf-life of 2 days was observed at ambient temperature (22–25°C).

Potential application

There is potential application for irradiation to improve the marketable life of mushrooms. Legal clearance for the irradiation of mushrooms is given in a number of countries (see Table 10, page 86). Marketing trials of irradiated mushrooms have taken place in the Netherlands (Heins, 1982) and America (Corrigan, 1993).

See also Fruit and vegetables; Sterilization.

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Mutagens

Mutagens are chemical substances that may cause damage to the genetic machinery of cells. A large number of mutagens occur naturally in many raw, cooked and otherwise processed foods. The presence of some level of mutagens in irradiated foods is to be expected (Schubert 1969; Kesavan and Swaminathan, 1971). There is no evidence that many of the naturally occurring mutagens constitute a significant health hazard, for instance by contributing to carcinogenicity. Together with the results of numerous animal feeding studies of irradiated foods, it is judged that mutagens that may be present in irradiated foods give no more cause for concern than those present in other foods (see ACINF, 1986).

See also Toxicology.

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Mutations

Ionizing radiation can cause mutations in *micro-organisms* through its action on *DNA*. Indeed, it is often used, in the laboratory, to deliberately induce mutations. Concern has therefore been expressed that the widespread irradiation of foods could lead to the accelerated production of mutants, some of which might have deleterious properties. It has also been suggested that radiation-tolerant mutants might be selected and, over a period of time, become so dominant as to reduce the efficiency of the process. However, although radiation-tolerant mutants have been produced under laboratory conditions, such mutations have not been observed under the practical conditions relevant to food irradiation, and are therefore judged not to constitute a problem.

The possibility of the induction of deleterious properties in *micro-organisms*, such as the enhancement of antibiotic resistance, increase in pathogenicity or in the ability to produce *toxins*, has been considered. However, in the numerous food irradiation studies that have been undertaken, such changes have not been observed and so are judged not to constitute a problem with respect to *bacteria*, *viruses* and *yeasts* (WHO, 1981).

Many *moulds* display far greater genetic variability than *bacteria* and *yeasts*, and changes such as enhanced mycotoxin production have been observed in laboratory studies, but not under conditions of commercial food irradiation.

See also Micro-organisms – Safety; Moulds.

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Mutton *see* Meat.

Mycotoxins *see* Moulds.

N

Nectarine (*Prunus nectarina*)

Irradiation is a potential method of controlling *insect* infestation in nectarines. Nectarines are commonly infested with the Mediterranean fruit fly. A radiation dose of 0.3 kGy, which would give good control of this pest, did not adversely affect the sensory quality of the *fruit* (Moy and Nagai, 1985; Moy, 1986). The *economic* benefits of irradiation as a quarantine treatment for nectarines, as an alternative to methyl bromide fumigation, have been evaluated (Forsythe and Evangelou, 1993).

Major post-harvest diseases of stone fruits are caused by the *moulds Monilinia fructicola* (brown rot), *Rhizopus stolonifer* and *Botrytis cinerea*. Cold storage inhibits the growth of *Monilinia* and *Rhizopus*. Doses in excess of 1 kGy, which would be effective for controlling fungal disease, are reported to cause *colour, flavour* and *texture* changes (Thomas, 1986). In addition, irradiation is reported to accelerate *ripening* of the *fruit*.

See also Fruit and vegetables; Insect disinfestation; Moulds.

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Nematode *see* Parasites.

Newcastle disease virus *see* Viruses.

Niacin (vitamin B5)

General

Major dietary sources of niacin include liver and red *meats, poultry, fish* and whole *cereal grains*. Like *riboflavin*, niacin is chemically relatively stable, e.g. to oxidation and to heat, thus surviving well in thermally processed foods.

The biologically active forms of vitamin B5, derived from niacin or nicotinic acid, are NAD (nicotinamide adenine dinucleotide) and NADP (nicotinamide adenine dinucleotide phosphate). These are co-factors for a wide range of important dehydrogenase and reductase enzymes so that deficiency brings about a variety of symptoms. These include intestinal disfunction, interference with nerve impulses, and lesions in the mouth and on the skin, leading to the disease pellagra.

Radiation sensitivity

Although slightly less stable to irradiation than *riboflavin* in simple aqueous solution, niacin has substantial radiation tolerance in foods. As has been observed with *riboflavin*, niacin levels in some foods rise on radiation, e.g. in *pork* and *chicken* (Fox *et al.*, 1989) and in bread made from irradiated flour (Diehl, 1980).

See also Vitamins.

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Nitrite reduction

The use of nitrite in bacon, ham and other cured *meat* products imparts *colour* and *flavour*, reduces oxidative changes and retards the growth of *Clostridium botulinum*. The addition of nitrite may lead to the formation of nitrosamines, which have been found to be carcinogenic. The amount of nitrite needed to control *C. botulinum* is greater than that needed to provide the typical *colour* and *flavour* of *meats*.

In bacon curing, a dose of 15–30 kGy enabled lower, safer levels of nitrite to be used (Urbain, 1986). Irradiation controls the growth of *C. botulinum* spores and nitrite was required only to maintain the *colour* of the product.

Reductions of greater than 50% or more were feasible. Treatment with a dose of 12–15 kGy (at -20°C) provided protection against growth of *C. botulinum* equivalent to that provided by a sodium nitrite concentration of 120 parts per million, typical of commercial processing (CAST, 1989). When only 20–40 parts per million of sodium nitrite were added, instead of 120 parts, the fried bacon had the same *colour* characteristic of the commercial product. In bacon irradiated at 30 kGy, nitrosamines were not detected, and the added nitrite was destroyed.

A reduction in nitrite concentrations in bacon and other cured *meat* products is shown in Table 15 (Wierbicki, 1981). Good quality products were obtained with normal cured colours. It has been suggested that irradiation may be used in the future, if legislation further reduces the amount of nitrite permitted in these products (Fink and Rehmann, 1994).

Radiation preservation of low nitrite bacon, using doses below 10 kGy, is technically feasible. Bacon in evacuated packages, containing 20–40 mg/kg of nitrite, irradiated at below 10 kGy, and stored at 4°C, had a shelf-life of greater than 90 days compared with 30 days for the control (Singh, 1988). When bacon containing 20 mg/kg was vacuum packed, frozen at -20°C and sterilized with 30 kGy, it was shelf-stable at room temperature for months to years.

Table 15 Radiation–sodium nitrite combinations for cured meats. (Irradiation temperature: -30+/- 10°C) (from Wierbicki, 1981)

Product	Non-irradiated mg/kg $NaNO_2$	Irradiated mg/kg $NaNO_2$	Dose (kGy)
Bacon	120	20	30
Ham	156	25 *	32
Corned beef	156	50	26
Frankfurter	156	50	32

* Plus 25 mg/kg $NaNO_3$

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Nut

General

Nuts contain substantial amounts of oils. Radiation accelerated *lipid* oxidation may result in undesirable *flavour* development. The effect of irradiation on nuts depends on dose and nut variety.

Irradiation of nuts to control *insect* pests has been considered as an alternative to the use of methyl bromide fumigation. Insects such as *Tribolium castaneum* and *Sitotroga cerealella* may infest walnut and pinenut; *Cadra cautella* and *Plodia interpunctella* infest almond and groundnut (Sattar *et al.*, 1989). Irradiation with doses up to 1 kGy is recommended for *insect disinfestation*, and is permitted in a few countries, including Israel and South Africa (see Table 10, page 86).

The sprouting and rooting of chestnuts can be inhibited using low radiation doses. There is legal clearance in Korea for this purpose (see Table 10).

Higher doses are required to control bacterial and *mould* spoilage, which cause significant *post-harvest losses* and aflatoxin development in nuts. This treatment increases the risk of *off-flavour* development. Reducing the radiation dose, by using a combination of heat and irradiation, may be effective against fungal infection in nuts (Farkas, 1990).

Pistachio (Pistacia vera)

Both *insects* and *mould* cause serious losses of the pistachio nut crop. The use of irradiation to control these pests, as an alternative to conventional insecticides and fungicides, has been investigated (Kashani and Valadon, 1984). No significant effects on *lipids*, *carbohydrates* or *protein* were detected in Iranian pistachio kernels irradiated up to a dose of 10 kGy.

In contrast, a radiation dose of 1.5 kGy, which gave an effective reduction in microbial load, caused rancidity even in vacuum-packed, frozen samples of pistachio nuts (Zehnder and Hartmann, 1982). It is suggested that radiation-induced rancidity is due to the high content of unsaturated fatty acids in pistachio nut lipids.

Chestnut (Castanea spp.)

Inhibition of post-harvest rooting and sprouting in chestnuts by irradiation has been reviewed by Thomas (1988). The recommended dose, which increases shelf-life, is 0.1–0.6 kGy. Doses in the range 0.5–1 kGy increase the sucrose content of the irradiated chestnuts. There is legal clearance for irradiation of chestnuts up to a maximum dose of 0.25 kGy in Korea.

Almond (Prunus dulcis)

The sensory quality of almonds irradiated at a dose appropriate for *insect disinfestation* has been investigated (O'Mahony *et al.*, 1985). Almonds, both raw and roasted, were irradiated at 1 kGy then tested after 6-months storage. Differences in *flavour* or mouth feel were not detected between irradiated and non-irradiated almonds. These results were confirmed by Narviaz *et al.* (1992). A slight decrease in odour intensity in almonds, treated with 1.5 kGy and 2 kGy, was reported.

Peanut/groundnut (Arachis hypogaea)

The groundnut or peanut is classed as a *legume*. *Lipid* peroxidation rate is lower in the groundnut than other nut species (Sattar *et al.*, 1989; 1991). The sensory quality of irradiated nuts was not adversely affected by doses up to 1 kGy, which are appropriate for *insect* infestation.

Radiation doses of the order of 5 kGy controlled the growth of *Aspergillus parasiticus* in peanuts (Chiou *et al.*, 1990; 1991). At this dose aflatoxins were still produced by surviving *mould*, but higher doses resulted in a change in nut *proteins* and a decrease in oil stability.

Walnut (Juglans regia)

Although it has been reported that peroxidation is higher in walnuts than in almond or groundnut (Sattar *et al.*, 1989), treatment of shelled walnuts at doses up to 1 kGy may not affect the sensory quality (Jan *et al.*, 1988).

Pinenut (Alpinus pinea)

Peroxidation rate is reported to be higher in pinenuts than almonds and groundnuts (Sattar *et al.*, 1989; 1991). However, there was no obvious deterioration in sensory quality up to 1 kGy.

Cashew nut (Anacardium occidentale)

There were no adverse effects on the sensory quality of cashew nuts, treated with doses of the order of 1 kGy, despite an increase in *lipid* peroxidation (Narviaz *et al.*, 1992). Higher doses caused a deterioration in *flavour* and acceptability, and a decrease in odour intensity.

See also Insect disinfestation; Legislation; Moulds.

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Nutrition

Most food preservation and decontamination procedures, including irradiation, cause some loss in the nutritional value of foods. Further losses generally occur during storage and during preparation for consumption (e.g. cooking). The specific chemical changes brought about in foods by irradiation include some that alter nutritional value, but the magnitudes of the changes are small when compared with the changes that result from the other procedures that are currently in use. This has led most expert groups to conclude that reduction in the nutritional quality of foods, resulting from the widespread use of irradiation, would be insignificant when considered within the diet as a whole (Elias and Cohn 1977; WHO, 1981, 1994; ACINF, 1986). However, most expert groups also recommend that the nutrient content of irradiated foods should continue to be monitored as such foods are introduced.

A problem with many of the literature reports on the effects of irradiation on food constituents is that the studies have used laboratory 'model' experiments, often with pure or relatively pure target substances, irradiated in water or buffers, etc. Whilst these studies are ideal for investigating the chemistry of the radiation-induced changes, it is very difficult to extrapolate from them to the situation in real foods. In real foods, many of the other components present, usually in large quantities, interact, quench and otherwise interfere with the reactions of the radiolysis-derived products. Consequently, the magnitude of the changes that occur in specific components in a food matrix are generally much less than those that are observed in the simpler laboratory studies (Josephson *et al.*, 1979).

In general, the nutritional values of the macronutrients in foods (e.g. the *carbohydrate*, *lipid* and *protein* components) are very little affected by *ionizing radiation*. Some of the micronutrients, including some *vitamins* and polyunsaturated fatty acids, are more sensitive but their sensitivity is very dependent on the nature of the food. At the 1 kGy dose level, which is in excess of insect disinfestation applications, virtually no nutrient depletion is generally measurable although reports of the rises and of falls in vitamin C levels have been reported in conflicting publications. At the 10 kGy level, the vitamins *ascorbic acid* (vitamin C), *thiamine* (vitamin B1), and *pyridoxine* (vitamin B6) are generally the most sensitive, but to extents that vary very much depending on the specific food (see specific vitamin entries).

See also Carbohydrates; Direct and indirect action of ionizing radiation; Lipids; Minerals and trace elements; Proteins; Vitamins.

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O

Oats *see* Cereal grains; Vitamins.

Off-flavours *see* Flavour; Sensory evaluation.

Oilseeds *see* Legumes.

Okra (*Hibiscus esculentus*); Lady's fingers
The *economic* benefits of using irradiation as a quarantine treatment for okra, instead of using methyl bromide, have been evaluated (Forsythe and Evangelou, 1993). Deterioration is accelerated above a dose of 1 kGy (Avadhani and Lian, 1985).

See also Insect disinfestation.

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Olive (*Olea europaea*)
Irradiation of olives in the range 1–4 kGy, appropriate for the control of decay, caused softening and increased susceptibility to *mould* growth (Bramlage and Couey, 1965). Radiation caused yellowing, as well as external and internal discolouration of the *fruits*.

Irradiation may have potential for the *insect disinfestation* of olives (CAST, 1989).

References
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Onion (*Allium cepa*)
For inhibition of sprouting leading to a reduction in storage losses, the recommended dose is 0.02–0.12 kGy.

Guidelines
A Code of Good Irradiation Practice for Sprout Inhibition of Bulb and Tuber Crops, ICGFI Document No. 8, 1991, is published by the International Atomic Energy Agency.

Treatment
Irradiation is an alternative treatment for the *inhibition of sprouting* of onions to the use of chemical sprout suppressants, such as maleic hydrazide or ethepon, or to cold storage. The effect of irradiation on bulb crops, including onions, has been reviewed by Matsuyama and Umeda (1983) and Thomas (1984). Irradiation is most effective as a sprout inhibitor when treatment is carried out in the dormancy period, preferably within 1 month of harvest, and no later than 2-months post-harvest. Storage losses due to dehydration and rotting are significantly reduced in irradiated onions for 8–10 months, in ambient conditions.

Irradiation has little or no effect on the odour or *flavour* characteristics of onions. In terms of appearance, radiation-induced inner bud darkening can be a problem. Darkening occurs irrespective of varietal differences, time of irradiation after harvest, dose and post-irradiation storage time and conditions. However, these factors can modify the intensity and extent of darkening. Discolouration is reduced by minimizing the time between harvest and irradiation. Bud darkening in irradiated onions is considered to be of little practical significance and processing characteristics are not adversely affected.

Potential application

Although it has been established that irradiation is a technologically feasible method of sprout inhibition, it may not be *economic*. The *economic* benefits of irradiation of onions have been evaluated (IAEA, 1993).

Legal clearance for the irradiation of onions is given in many countries (see Table 10, page 86). There have been a number of commercial trials of onion irradiation in tropical countries (IAEA, 1992 and see Table 11, page 98). A high degree of consumer acceptance of irradiated onions was recorded in marketing trials in Argentina (Urioste *et al.*, 1990). Commercial irradiation of onions in Hungary took place five years ago (see Table 5, page 32), but does not take place at present.

See also Colour; Detection; Inhibition of sprouting; Legislation; Market trials.

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Orange (*Citrus senesis*)

For insect disinfestation from fruit flies, and for control of storage caused by fungal pathogens, the recommended dose is less than 1 kGy.

Insect disinfestation

Fruit flies, such as the Mediterranean fruit fly and Queensland fruit fly, are a serious pest of oranges and tangerines. Chemical fumigants such as ethylene dibromide and methyl bromide, which are used as disinfestation treatments for *citrus fruit*, are banned or are being phased out because of a potential health risk. Cold treatments are also used. Irradiation is a potential method of quarantine treatment for oranges.

Although a minimum dose of 0.15 kGy has been recommended as the effective dose for preventing adult emergence of fruit flies, a higher dose is needed to minimize the problems of egg hatch. A radiation dose of 0.5–0.75 kGy has been recommended for oranges (Moy *et al.*, 1992). The quality of Valencia oranges was retained at this dose. Valencia and Navel oranges treated with a doses of 0.7–1 kGy, and stored at 7°C, were well preserved for at least 6 weeks (Moy and Nagai, 1985). The use of a combination of waxing, heat treatment (50°C for 5 minutes), and 0.7 kGy for oranges was effective (Montalban *et al.*, 1993).

Control of fungal spoilage

Early research focused on the possibility of using irradiation to prevent post-harvest *mould* spoilage of oranges (Thomas, 1986). The major fungal pathogens associated with oranges include *Diplodia*, *Phomopsis* and *Alternaria* spp., which cause stem end rot, and green and blue moulds, caused by *Penicillium* spp. However, to control fungal decay, an effective dose needs to be in excess of 1 kGy and this results in unacceptable damage to the peel of the *fruit*.

Product characteristics

An important limiting factor in the practical application of irradiation to oranges is the injury caused to peel tissues, in the form of skin pitting, necrosis, dark spots and bronzing. This occurs above a dose of approximately 1 kGy; severity of peel damage increases with dose. The threshold radiation dose may be modified by several factors such as variety, maturity at harvest, time delay between harvest and irradiation, environmental conditions during *fruit* growth, and post-irradiation storage time and temperature (Thomas, 1986). In general, it is recommended that fully ripened oranges are treated, at 7°C or below, at doses below 1 kGy in combination with a hot water dip (approx 50°C for 5 minutes). The hot water dip reduces the incidence of *mould* infection on storage.

Irradiated oranges may be softer and easier to peel than untreated *fruit*; these effects increase with higher storage temperatures and with increasing dose (Moy *et al.*, 1992). Organoleptic quality, *ascorbic acid*, total acids and total soluble solids were maintained at a doses of 0.75 kGy at 7°C, and 0.5 kGy at 21°C (Nagai and Moy, 1985). *Flavour* of the *juice* of oranges may be discriminated from that of the untreated *fruit* by doses in the range 0.3–0.6 kGy (O'Mahony and Goldstein, 1987).

Potential application

Radiation disinfestation of oranges appears to be technically feasible. Market testing of irradiated oranges has been reported in China (Qixun *et al.*, 1991) and in the USA (Corrigan, 1993).

See also Citrus fruit; Fruit and vegetables; Insect disinfestation; Legislation; Juice; Market trials.

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Organoleptic *see* Sensory evaluation.

Oriental fruit fly *see* Insects.

Overall average dose *see* Dose distribution.

Overdose ratio *see* Dose distribution.

Oxygen

General

Irradiation of foods generates oxygen-containing, highly reactive, free radicals, whether or not oxygen is present during irradiation, because most of these radicals are derived more or less directly from the radiolysis of water. Nevertheless, the radiation resistance of *microorganisms* in a food is generally greater when the food is vacuum-packed or packed in nitrogen prior to irradiation than when it is exposed to air (see Figure 11, page 105) (Goldblith, 1971). Exceptions have been reported (Patterson, 1988 and Table 18, page 131).

At the same time, vacuum or nitrogen packing will reduce the *off-flavours* generated during the irradiation of certain foods, and this may outweigh the disadvantages of increased microbial resistance.

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P

Packaging

Foods are usually pre-packaged prior to irradiation. This prevents recontamination by *insects* or *micro-organisms*, in addition to promoting optimum food quality and shelf-life. Packaging materials are exposed to radiation during the treatment. This can lead to radiation-induced degradation of the packaging material, and interactions between the material and the food product.

Information on the effects of *ionizing radiation* on packaging materials comes from research in commercial areas, such as the sterilization of packaged medical products and the modification of the properties of plastics, e.g. shrink-wrap film. Doses used in these applications are at least ten times higher than those needed for food irradiation.

Radiation penetration of the packed product

Irradiation can be used to treat a range of different foods, which implies a wide range of packaging materials, sizes and shapes. The size and shape of the package needs to be considered with respect to the irradiation facility. Characteristics of the product transport system and the type of radiation source are important factors. For example, *gamma rays* and *X-rays* can penetrate pallet loads of prepackaged bulky items, such as *spices* or *onions* (see Figure 5, page 56). High energy electrons, because of their limited penetration, are suited to treating thin packages of food (see Figure 7, page 56). The limited penetration of high velocity electrons precludes secondary or bulk packaging. *Dose distribution* within the packaged product must be determined using *dosimeters*.

Effect of irradiation on rigid containers

Rigid metal containers, such as tin and aluminium cans, are resistant to radiation at doses that are used for radiation preservation of foods. A number of enamels and end-sealing compounds have been recommended for use with irradiated food (Killoran, 1983). Similarly, the physical and chemical properties of glass and ceramic materials are unaffected, although brown discolouration is observed on irradiation even at doses less than 3 kGy. This can be avoided by addition of cerium to the glass melt, although this is costly. The brown discolouration is reversible on heating the material.

Packaging of individual packs into secondary containers of fibre board or paperboard, prior to irradiation, is attractive economically. Physical deterioration, as measured by bursting strength and puncture resistance, of paper and cellulosic material caused by irradiation may not be significant much below 10 kGy (Killoran, 1983). The loss in strength may have little practical consequence if paper is laminated to polyethylene or foil.

Effects of irradiation on polymeric films

The majority of primary packaging materials for irradiated foods will be some form of plastic polymeric film, or laminate. *Ionizing radiation* causes cross-linking, degradation and gas evolution in plastics. Experimental results show that a number of factors affect the stability of polymers to irradiation:

- composition of the packaging film;
- processing history, e.g. formulation, laminate;
- conditions of treatment, e.g. temperature, presence of oxygen;
- irradiation dose;
- dose rate;
- food simulant.

The complexity of these parameters is likely to be the cause of the diversity of results found in the literature (El Makhzoumi, 1994). The effects of irradiation on the physical, chemical and sensory properties of plastic food packaging material have been reviewed (Buchalla *et al.*, 1993a, b). The safety of packaging material in contact with irradiated food is critical.

Physical effects on polymeric films

Cellulose-based materials are the least stable of flexible films, with a threshold for damage below 10 kGy;

generally, changes to organic polymers are not significant below 60 kGy.

Irradiation, at doses appropriate for food irradiation, does not cause deterioration in the mechanical properties of plastic films, or significantly affect permeability or barrier properties (Buchalla *et al.*, 1993a). The mechanical properties of films, including polyethylene terephthalate (PET), low-density polyethylene (LDPE), and high-impact polystyrene (PS), are little affected by doses of 15 kGy, or even up to 30 kGy (Senior, 1992). In addition, changes in heat seal performance and coloration were within normal limits for the films, at doses up to 15 kGy. However, there may be fluctuations in permeability to oxygen and carbon dioxide of LDPE, treated with doses less than 10 kGy (Deschenes, 1992). Such changes in permeability could be significant for stored *fruit* and *vegetables*.

Chemical effects on polymeric films

Evolution of gases and volatile compounds from irradiated polymers can occur at 10 kGy or less, depending on a number of factors, including type of film, dose, presence of oxygen and food simulant. The toxicological implications and possible packaging-induced taint development in irradiated foods need to be considered.

The main products formed during irradiation under vacuum, are hydrogen, methane, and, for chlorine-rich polymers, hydrogen chloride (Buchalla *et al.*, 1993a). In the presence of oxygen, carbon dioxide and carbon monoxide are formed. A number of volatiles are evolved, including hydrocarbons, alcohols, aldehydes, ketones and carboxylic acids. Hydrocarbons, ketones and aromatic compounds are formed from LDPE, oriented polypropylene (OPP), and PET, after electron beam irradiation at 5 kGy (El Makhzoumi, 1994). In LDPE, 22 compounds were formed; in OPP, 40 compounds; and only acetone was identified for PET.

Safety of polymeric films

Packaging materials for use during irradiation of prepackaged foods must be safe. One essential requirement is that no *induced radioactivity* is detectable in the packaging material itself. In addition, there should be no health hazard associated with the migration of toxic compounds from the packaging material to the food. In general, for doses up to 25 kGy, no increases in global migration into food simulants have been identified (Buchalla *et al.*, 1993b).

Polymers including PVC, PE and polypropylene (PP), contain antioxidants such as phenolic and arylphosphite compounds; organotin stabilizers are present in PVC to prevent thermal degradation. The effects of irradiation on the degradation and migration of these additives have been extensively studied by Allen *et al.* (1990) and Bourges *et al.* (1992). There is evidence to suggest that there can be a 50% degradation of antioxidants at 10 kGy, depending on the nature of the antioxidant and the polymer. However, *gamma irradiation* leads to a decrease in the degree to which hindered phenol antioxidants migrate from polyolefins into fatty food simulants. Degradation products of antioxidants in food-contact polymers, treated with *electron beam* radiation, have been identified (Bourges *et al.*, 1993). Migration of these products from commercial PP into food simulants takes place at 10 kGy and below.

On the basis of results using food simulants in the 1960s, the Food and Drug Administration in the United States has approved a range of films as safe for use for *gamma irradiation* up to 10 kGy or 60 kGy (Welt and Welt, 1993) (Table 16). This list was amended, in February 1989, to include ethylene vinyl acetate copolymers (CFR 177.135) up to a dose of 30 kGy (Derr, 1993). The films approved by the FDA are single films that do not necessarily satisfy modern packaging needs. The effects of irradiation on laminated films and the significance of degradation and migration of additives need to be established for foods irradiated at low radiation doses.

Table 16 Summary of FDA-approved polymeric films 21 CFR 179.45).

Material	Description of approved material (FDA reference number)	Approved maximum radiation dose (kGy)
Nitrocellulose or vinylidene chloride coated cellophane	177.120	10
Wax coated paperboard	176.170	10
Glassine paper	176.170	10
*Polyolefin film	177.152	10
+Kraft paper	176.170	0.5
*Polystyrene film	176.163	10
*Rubber hydrochloride film	175.300	10
Nylon 11	177.150	10
*Vinylidene chloride-vinyl chloride copolymer film	175.320	10
*Polyethylene film	177.152	60
*Polyethylene terephthalate film	177.163	60
*Polyiminocypropyl (nylon 6)	177.150	60
*Vinyl chloride-vinyl acetate copolymer film	175.320	60
Vegetable parchment	179.45	60

* May contain specified additives and coatings.
+ Regulations state that this is used only as a container for flour.

Sensory effects on polymeric films

The formation of gases and volatiles in irradiated packaging films may lead to the development of unpleasant odours and *flavours* in food products. Since irradiating food can lead to *off-flavours* and off-odours, isolation of those taints that are due entirely to packaging material itself is difficult. Taint development using food simulants has been used to screen a range of food-grade packaging materials.

Development of off-odours and taint transfer has been observed with various plastics, including PE (Buchalla *et al.*, 1993b). However, in PE, PP, and PET, there was no evidence for taint transfer at doses of the order of 3 kGy (Kilcast, 1990). Nitrocellulose-coated cellulose and PVC were found to carry risk of tainting food. The relevance of the results to the packaging of real foods was not determined.

Packaging irradiated foods

Choice of packaging material will be influenced by characteristics of the food product and the objective of the treatment. *Combination treatments*, involving irradiation, heat and modified atmosphere packaging, may make additional demands on packaging material.

Packaging materials for irradiated foods need to conform to the following criteria:

- functional protective properties must be resistant to radiation;
- no transfer of toxic substances to food;
- no transmission of off-odours or taint to food;
- retention of seal strength and barrier properties of films.

It needs to be established that modern food packaging materials, which tend to be multi-layer films with different barrier properties, conform to these criteria. Currently, the effects of irradiation on laminates, and on seal strength and adhesives are unclear.

See also Applications; Dose distribution; Fish; Fruits and vegetables; Insect disinfestation; Meat; Poultry; Spices; Sterilization.

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Pantothenic acid

General

Major dietary sources of pantothenic acid include liver, kidney, yeast, *egg* yolks, *milk*, bran, *nuts* and, in lesser quantities, a wide variety of other foods. Pantothenic acid is chemically sensitive to extreme pH values, but stable at the pH of most non-acidified foods. *In vivo* it makes up a part of coenzyme A, which is involved in all major acyl group transfers in cells. The results of deficiency are therefore diverse and lead to general illness.

Radiation sensitivity

Many studies with irradiated foods have demonstrated the substantial radiation resistance of pantothenic acid. For example, it was not significantly destroyed by irradiation of *beef* at nearly 30 kGy (Richardson *et al.*, 1961), of clam meat at 45 kGy (Brooke *et al.*, 1964) or of *egg* yolk (frozen) at 50 kGy (Kennedy, 1965).

Small losses (about 10%) of pantothenic acid occurred on irradiation of wheat at 2 kGy (Kennedy, 1965) but the general picture is of resistance equivalent to that of the most radiation-resistant vitamins, at realistic doses in actual foods.

See also Vitamins.

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Papaya (*Carica papaya*)

For insect disinfestation and for shelf-life extension by delaying ripening and senescence, and control of fungal disease, the recommended dose is up to 0.75 kGy (in combination with a hot water dip).

Insect disinfestation

The possible application of irradiation, as an alternative method of *insect disinfestation*, has been prompted by recent restrictions on the use of chemical fumigants. The use of irradiation as a quarantine treatment for papaya, originating from Hawaii, has been approved by the FDA (FDA, 1989).

Oriental, Mediterranean and melon fruit flies are serious pests of papaya. A minimum dose of 0.15 kGy is recommended for the control of these *insects*. *Packaging* in fly-proof containers is essential. The *flavour* and aroma of papaya (variety 'Solo') irradiated at 0.25–1 kGy was unchanged compared with fumigated controls (Moy and Nagai, 1985). A dose of 0.3 kGy is recommended for quarantine treatment of 'Esotika' papayas (Vijaysegaran, 1991).

Guidelines

A Code of Good Irradiation Practice for Insect Disinfestation of Fresh Bananas, Mangoes and Papayas, ICGFI Document No. 1, 1991, is published by the International Atomic Energy Agency.

Shelf-life extension

Delayed *ripening* of papaya fruit can be achieved with doses up to 0.75 kGy (Thomas, 1986). The maximum dose that can be tolerated by *fruits* in the green preclimacteric stage is 1 kGy, above which *fruits* develop surface scalding and bitter *off-flavours*. At the edible ripe stage, irradiated *fruits* are firmer than unirradiated edible ripe ones. The firm *texture* is an advantage for handling during transport and marketing.

Decay caused by *moulds* can be reduced by combining irradiation with a hot water dip. A hot water dip, typically 10 minutes at 50°C, followed with minimal delay by irradiation at 0.75 kGy, increased the shelf-life of papayas significantly (3 days or more) if refrigerated for 3 weeks at 10°C and maintained at 21–23°C, for 6–7days (Moy *et al.*, 1985). After a combination of hot water dip and irradiation at 0.75–1 kGy, no significant differences in *flavour* or aroma were reported (Moy and Nagai, 1985). Due to *ripening* delay, *texture* was firmer and *fruits* were slightly lighter in *colour* compared with untreated fruits. Significant loss of nutrients does not occur in papaya irradiated at doses below 1 kGy (Thomas, 1986).

Potential application

Legal clearance for the irradiation of papayas for disinfestation and shelf-life extension is given in a number of countries, including Bangladesh, Brazil, China, South Africa, Syria, Thailand and the USA (see Table 10, page 86). Commercial feasibility studies and market trials of irradiated papaya have been reported in South Africa (Broderick and van der Linde, 1981) and the USA (Moy, 1987; Bruhn and Noell, 1987) (see Table 11, page 98).

See also Insect disinfestation; Legislation; Market trials; Ripening and senescence; Vitamins.

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Parasites

General

Food-related parasitic diseases of humans and livestock exist to some degree in all parts of the world. Parasitism causes a range of physiological problems, infant deformity and mortality. Hygiene and education, and a change in eating habits, are recognized as primary control measures. The *economic* losses caused by major parasitic diseases in different countries are discussed in Roberts and Murrell (1993).

Parasites are associated with certain raw and partially processed foods. Irradiation of these foodstuffs to control parasites has been considered. Research into the effects of radiation doses on specific organisms has been reviewed by King and Josephson (1983), CAST (1989), IAEA (1993).

Parasites in fish

Fish-borne, snail-borne and crustacean-borne parasitic diseases are found worldwide, with a high prevalence in Asia. This is primarily due to consumption of raw, undercooked and fermented *fish*. Infection with liver flukes, e.g. *Opisthorchis viverrini* and *O. felineus*, and the Chinese liver fluke *Clonorchis sinensis*, is common. High infection rates of *Gnathostoma spinigerum*, a type of liver fluke, are found in Thailand. Prolonged infections of these parasites can lead to liver damage.

In general, low radiation doses can be used to control liver flukes (see Table 17). Low doses are also effective against *Paragonimus* spp. found in uncooked crustaceans, crabs and crayfish. Other parasites in *fish* require higher radiation doses for their control. Anisakiasis is caused by consuming the nematode *Anisakis* spp. found in marine *fish* and molluscs. Infections in humans occurs worldwide, but most human disease is found in Japan in the form of intestinal disease. A lethal dose of 6–10 kGy is required for inactivation of *Anisakis* spp. Uncooked molluscs and *shellfish* are sources of the parasite *Angiostrongylus* spp., which is also relatively radiation resistant. The use of a sublethal dose that could render the larvae of these parasites non-infectious, or non-pathogenic, may have potential (Diehl, 1990). If radiation doses are too high to be compatible with organoleptic quality, a combination of irradiation plus freezing or heating could be an effective control measure.

There is potential for the use of irradiation to treat *fish* and *shellfish* to control parasites, in order to improve the safety of foods for local consumption or export (IAEA, 1993). Irradiation control measures could be implemented using mobile irradiation units or treatment at central locations.

Table 17 The effect of irradiation on parasites (references: IAEA, 1993; Roberts and Murrell, 1993).

Parasite	**Mode of infection**	**Dose (kGy)**	**Effect of irradiation**
Clonorchis spp.	Chinese liver fluke, occurs in raw fish	0.15	*In vitro* minimum effective dose
Opisthorchis viverrini	Liver fluke found in contaminated raw, pickled or smoked fish	0.1	*In vitro* minimum effective dose
Paragonimus spp.	Parasitic worm found in crabs and crayfish in Asia	0.1	*In vitro* minimum effective dose
Gnathostoma spinigerum	Parasitic worm found in raw, undercooked or fermented fish	7	Reduces worm recovery rate in mice
Angiostrongylus cantonensis	Parasitic worm found in uncooked molluscs, shellfish	2	Minimum effective dose
Anisakis spp.	Nematode is ingested if fish is eaten raw or slightly salted	2–10	Reduces infectivity of larvae
Trichinella spiralis	Nematode occurs in raw or inadequately cooked pork	0.3	Minimum effective dose
		0.3–1	FDA permitted dose to control trichina in pork
Toxoplasma gondii	Consumption of undercooked meat or poultry; or contact with infected animals	0.7	Minimum effective dose for fresh pork
Cysticercus bovis (*Taenia saginata*, in man)	Tapeworm found in uncooked or undercooked beef; causes taeniasis	0.3	Preliminary minimum effective dose
Cystericercus cellulosae (*Taenia solium*, in man)	Tapeworm found in pork	0.3	Preliminary minimum effective dose

Parasites in meat

Trichinosis, caused by *Trichinella spiralis* infection of pigs, is a significant food safety problem in certain countries. Current prevention strategies include *meat* inspection, treatment of pork by freezing, heating, smoking or curing, and improvement in pig rearing practices to prevent *T. spiralis* in herds. In the USA, irradiation of pork for trichina control is permitted with a minimum dose of 0.3 kGy and a maximum of 1 kGy (Engel *et al.*, 1988).

Toxoplasma gondii is one of the most widespread parasitic infections. It is particularly serious in pregnant women, since it is responsible for congenital malformations in infants. Sources of infection for humans are cats, and raw or undercooked *meat*, beef, mutton and particularly pork. Since *T. gondii* is easily inactivated in processed pork by heating, freezing or curing, the potential for irradiation treatment is for fresh pork, only. As a general recommendation for pork, control of *T. spiralis* and *T. gondii* can be achieved by a minimum effective dose of 0.7 kGy (IAEA, 1993 and Table 17), although the effectiveness of doses lower than this level has been demonstrated (Murrell and Dubey, 1991).

Cysticercosis in cattle and taeniasis in humans are serious diseases found worldwide. Taeniasis/cysticercosis is caused by *Taenia saginata* and *T. solium*. It is prevalent in Mexico, central and east Africa, Asia, south and central America. The infections are caused by poor sanitary conditions and consumption of raw and undercooked pork. Methods of interrupting the life cycle of the parasite have been implemented, including freezing, cooking, drying, salting and mincing *meat*. Doses below 1 kGy may be useful in preventing development of the parasite in humans; a minimum effective dose has not yet been confirmed (IAEA, 1993).

Potential use

The *economic* losses caused by food-borne parasitic diseases worldwide are high. Irradiation of fresh *meat* could reduce the incidence of parasitic disease, at low radiation doses, which would not compromise food quality (Roberts and Murrell, 1993). However, it has not been established whether this treatment is a cost-effective method of disease reduction.

In the USA, irradiation of pork to control trichina is specifically permitted (see Table 10, page 86), but is not used commercially. In several countries, irradiation of *meat* and *fish* is permitted to reduce microbial load. The dose required for this application is sufficiently high to control many parasites.

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Pasta *see* Cereal products.

Pea (*Pisum sativum*)

Radiation doses in excess of 3 kGy controlled *mould* growth in pea pods (Salunkhe, 1961). The peas became softer and sweeter as the radiation dose increased.

See also Legume.

Reference

Salunkhe, D.K. (1961) Gamma radiation effects on fruits and vegetables, *Economic Botany*, **15**(1), 28–56.

Peach (*Prunus persica*)

Irradiation could be used for insect disinfestation and control of fungal diseases.

Insect disinfestation

The possibility of using irradiation to control *insect* infestation in peaches has been considered. A radiation dose of 0.5 kGy is recommended for the control of the Mediterranean fruit fly in peaches (Moy *et al.*, 1992). Overall *fruit* quality was preserved in the 0.3–0.75 kGy range. Differences in *colour* between control and irradiated *fruits* were detected at 0.3–0.5 kGy and small differences in *flavour* at 0.3 kGy; *texture* changes occurred at 1 kGy. O'Mahony *et al.* (1985) found the threshold for *flavour* change in the range 0.65–0.75 kGy. The effects of irradiation on the sensory quality of peaches may reflect differences in peach varieties, *fruit* maturity and conditions post-irradiation, e.g. refrigeration, *packaging*.

Control of fungal diseases

Major post-harvest disease in stone fruits is caused by the *moulds Monilinia fructicola* (brown rot), *Rhizopus stolonifer* and *Botrytis cinerea*. Cold storage inhibits the growth of *Monilinia* and *Rhizopus*. Doses in excess of 1 kGy, which would be effective for controlling fungal disease in peaches, resulted in softening, changes in *flavour* and enhanced pigmentation (Thomas, 1986). Irradiation at doses above 1 kGy accelerated *ripening* in peaches. A *combination treatment* of a hot water dip and a lower radiation dose could be a feasible way of controlling fungal development with insignificant *fruit* damage.

Potential application

The *economic* benefits of irradiation as a quarantine treatment for peaches, as an alternative to methyl bromide fumigation, have been evaluated (Forsythe and Evangelou, 1993).

See also Combination treatment; Fruit and vegetables; Insect disinfestation; Moulds; Ripening and senescence.

References

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Peanut *see* Nut.

Pear (*Pyrus communis*)

Irradiation could be used for insect disinfestation and for extension of storage life by delayed ripening and control of fungal disease.

Insect disinfestation

Irradiation has potential application for the control of *insects* in pears. Control of fruit flies can be achieved with a minimum dose of 0.15 kGy, but a minimum of 0.25 kGy is required for codling moths. Evidence suggests that the sensory qualities of irradiated pears would not be affected at low radiation doses (Thomas, 1986).

Control of storage life

Doses in excess of 1 kGy are required to control *mould* growth by *Penicillium* and *Botrytis* spp. and to delay *ripening* in pears (Thomas, 1986). *Fruit* response to radiation depends on variety, dose, and conditions, such as harvest maturity. When unripe (pre-climacteric) pears were irradiated at 1–2 kGy, a delay in *ripening* was commonly observed. After treatment, there was a decrease in firmness that was masked by subsequent radiation-induced inhibition of softening during storage and *ripening*. The risk of softening, *flavour* loss, the development of dryness and mealiness, and abnormal *ripening* increased with increasing radiation dose.

The use of a combination of heat treatment (45°C for 5 minutes), followed by a dose of 0.5 kGy, prevented the rotting of unripe pears (Stegeman 1982). *Ripening* and senescence of *fruit* were delayed.

Potential application

More effective alternatives to irradiation are available to delay *ripening* and control fungal infection in pears. However, irradiation could be used as a *insect disinfestation* treatment (Meheriuk and Scholberg, 1990).

Marketing trials of irradiated pears, treated at doses of 0.2–0.8 kGy, have taken place in China 1985–87 (Qixun *et al.*, 1991) (see Table 11).

See also Combination treatment; Fruit and vegetables; Insect disinfestation; Moulds; Ripening and senescence.

References

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Pectin and cellulose

Research into the effects of irradiation on pectin and cellulose is reviewed by Diehl (1983). Pectins and protopectins are more sensitive to radiation damage than cellulose or hemicellulose. The physical and chemical properties of dry cellulose are not significantly affected below 10 kGy, or of dry pectin below 5 kGy. Above these doses, a decrease in solution\viscosity occurs. *Apple* pectin was more susceptible than *citrus fruit* pectin (Dzamic and Jankovic, 1966).

Irradiation of pectin in solution, with doses as low as 0.2 kGy, resulted in a reduction in viscosity, which increases with dose (Ayyad *et al.*, 1990; Dzamic and Jankovic, 1966). The practical consequences of pectin degradation are softening of *fruit* and *vegetables* at doses as low as 0.5 kGy.and, at higher doses, an increased *juice* yield of *fruit* and a reduction in cooking time of *dried vegetables* (Kiss *et al.*, 1974).

In a study of the effects of radiation on *cucumber* pickles (Howard and Buescher, 1989), softening of the product was associated with altered solubility characteristics of pectic substances at 1 kGy. Disturbance of the calcium-pectin association is cell walls has been related to softening of *fruit* and *vegetables*. Soaking *apples* and *pears* in a solution of calcium chloride prior to irradiation resulted in an improvement of *fruit* firmness after irradiation (Kovacs *et al.*, 1988).

See also Carbohydrates; Fruit and vegetables; Texture.

References

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Penicillium *see* Moulds.

Pepper *see* Capsicum; Spices.

Peptide *see* Protein.

Persimmon (*Diospyros kaki*); date plum, sharon fruit, kaki fruit

The effect of irradiation on the Japanese persimmon has been reviewed by Thomas (1988). Doses above 1 kGy accelerated *ripening* of persimmons, with the astringency of the *fruit* decreasing and softening increasing. Irradiation resulted in a reduction in tannin content of the *fruit*.

See also Legislation.

Reference

Thomas, P. (1988) Radiation preservation of foods of plant origin. Part VI. Mushrooms, tomatoes, minor fruits and vegetables, dried fruits, and nuts, *CRC Critical Reviews in Food Science and Nutrition*, **26**(4), 313–58.

Pesticide

There have been concerns that irradiation of foods containing pesticide residues could create a health risk. The FDA has calculated the amounts of *radiolytic products* that would be expected to be formed, if foods containing pesticide residues were irradiated at a dose of 1 kGy. For a pesticide residues of the order of 1 part per million (an average level), the calculated total yield of all *radiolytic products* was considered to be 'virtually nil' (ICGFI, 1991). On the basis of these results, it was concluded that pesticide residues do not pose a health hazard.

Reference

ICGFI (1991) *Facts about Food Irradiation*, International Consultative Group on Food Irradiation, Vienna, pp. 21–2.

Pet foods *see* Animal diets.

Phospholipids *see* Lipids.

Photostimulated luminescence

Like *thermoluminescence*, photostimulated luminescence results from the emission of light photons, which are derived from *free radicals* formed following irradiation and trapped in solid foods. However, in place of heat to stimulate emission, a high energy pulse of laser light is employed, with advantages of specificity and lower background count (Sanderson *et al.*, 1994).

See also Detection.

Reference

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Pigment *see* Colour.

Pineapple (*Ananas comosus*)

Pineapples are largely unaffected by low radiation doses, of the order of 0.5 kGy, which would be suitable for controlling *insect* infestation (Thomas, 1986). Treatment may result in delayed *fruit* senescence. Doses above 0.5 kGy caused skin darkening and discolouration of the core of pineapples (Avadhani and Lian, 1985). There is evidence for the presence of cytotoxic substances in *fruit* irradiated above 1 kGy (Thomas, 1986).

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Pinenut *see* Nut.

Pistachio *see* Nut.

Plum (*Prunus* spp.)

The *economic* benefits of irradiation as a quarantine treatment for plums, as an alternative to methyl bromide fumigation, have been evaluated (Forsythe and Evangelou, 1993). A radiation dose of 0.5 kGy is recommended for the control of the Mediterranean fruit fly in plums (Moy *et al.*, 1992). This treatment did not adversely affect the sensory quality of the *fruit*. Differences in *colour*, between treated and untreated *fruit*, were detected at 0.5 kGy, and in *texture*, at 0.5–1 kGy.

Major postharvest diseases of stone fruits are caused by the moulds *Monilinia fructicola* (brown rot), *Rhizopus stolonifer* and *Botrytis cinerea*. Cold storage inhibits the growth of *Monilinia* and *Rhizopus*. Doses of 1 kGy, which would be effective for controlling fungal disease, result in *colour* and *texture* changes in plums (Moy *et al.*, 1983).

See also Fruit and vegetables; Insect disinfestation; Moulds; Ripening and senescence.

References

Forsythe, K.W. and Evangelou, P. (1993) Costs and benefits of irradiation and other selected quarantine treatments of fruit and vegetable imports to the United States of America, in *Cost-benefit aspects of food irradiation processing*, Proceedings of a IAEA/FAO/WHO symposium, Aix-en-Provence, March, 1993, International Atomic Energy Agency, Vienna, pp. 271–89.

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Poliovirus *see* Viruses.

Polymers

The reaction of polymers in foods (e.g. high molecular weight *carbohydrates*, nucleic acids, *proteins*) to radiation may result in very large physical changes because, for example, a small number of chain scissions in a large molecule may bring about large changes in its molecular weight. However, the results of irradiation on a particular polymer are not easily predictable and vary greatly with the nature of the molecule (Diehl, 1983). For example, if irradiation ruptures cross-linkages, then it is commonly observed that the polymer 'softens' or gel strength is reduced. However, if irradiation induces coupling, i.e. via increased cross-linking, then 'hardening' may result.

See also Carbohydrates; DNA damage; Gelling agents; Proteins.

Reference

Diehl, J.F. (1983) Radiolytic effects in foods, in *Preservation of Food by Ionizing radiation*, Vol. I, (eds E.S. Josephson and M.S. Peterson) CRC Press Inc, Boca Raton, Florida, pp. 279–357.

Polyploidy

A report that undernourished children, who had been fed irradiated wheat, showed a high incidence of polyploidy (multiple chromosomes) in their peripheral lymphocytes (Bhaskaram and Sadasivan, 1975), gave rise to concern in the late 1970s. This followed reports of similar changes in mice, rats and later, monkeys (Vijayalaxmi and Sadasivan, 1975; Vijayalaxmi, 1978). Since then, further studies (e.g. George *et al.*, 1976) have failed to confirm the relationship of polyploidy to the ingestion of irradiated food (summarized in Brynjolfsson, 1988), but the issue continues to be stated by some authors as a cause for concern.

A major re-examination and rat feeding research study by Maier *et al.* (1993) indicated that the earlier results probably could be explained by an adaptive mechanism to food restriction that occurs in malnourished individuals. This adaptation includes minor changes in ploidy, e.g. in liver cells, and changes in cell cycling of bone marrow cells. They concluded that a spindle poisoning activity of radiolytic byproducts of wheat irradiation can be excluded, and that the consumption of irradiated wheat does not pose any health risk to humans.

See also Toxicology.

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Polysaccharide *see* Carbohydrate; Starch; Pectin and cellulose; Polymers.

Pome fruit *see* Apple; Pear.

Pork *see* Meat.

Post-harvest losses

It has been estimated that post-harvest losses can exceed 50% for *fruits* and *vegetables* and 10% for *cereal grains* and *legumes* (Anon, 1993). In developing countries, in particular, large quantities of food are lost due to post-harvest *insect* infestation, bacterial or fungal contamination, and physiological activities, e.g. sprouting, *ripening* and senescence. Irradiation could be an alternative method, or a complimentary method to existing technologies, of reducing post-harvest losses in *dried foods*, such as *cereals*, *legumes*, and *fruits* and *vegetables* (Anon, 1989).

References

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Anon (1993) Report and recommendations of a working group, in *Cost-benefit Aspects of Food Irradiation Processing*, Proceedings of an IAEA/FAO/WHO International Symposium, Aix-en-Provence, p. 481.

Potato (*Solanum tuberosum*)

For reduction in storage losses due to inhibition of sprouting, the recommended dose is 0.05–0.15 kGy.

Guidelines

A Code of Good Irradiation Practice for Sprout Inhibition of Bulb and Tuber Crops, ICGFI Document No. 8, 1991, is published by the International Energy Agency.

Treatment

Chemical inhibitors, such as isopropyl-n-phenylcarbamate (IPC) or methyl ester of naphthalene acetic acid (MENA), are used to inhibit sprouting in potatoes. In addition, low-temperature storage is effective. Irradiation could be used as an alternative to traditional methods to inhibit sprouting in potatoes.

The effectiveness of irradiation for sprout control depends on dose, potato variety and time of application (Matsuyama and Umeda, 1983; Thomas, 1983). In the dose range 0.05–0.15 kGy, sprouting is inhibited for 6–8 months with minimal losses. Sprouting is suppressed regardless of storage temperature ranging from 10°C to tropical ambient temperatures of 37°C (Thomas, 1983).

Treatment should take place within a 1–3 month dormancy period for maximum effect. However, a 2–3 week time delay, after harvesting, is required for healing mechanical damage incurred during harvesting. Irradiation interferes with suberization (wound healing) and can lead to increased rotting through microbial invasion of the tissue at locations of injury (*Fusarium* rot). This can be exacerbated by doses in excess of 0.15 kGy.

Product characteristics

Flavour and *texture* of irradiated potatoes are unaffected at appropriate radiation doses. However, darkening of potato flesh, after cooking, is a consequence of irradiation treatment. The extent of discolouration is influenced by cultivation conditions, variety and storage time. Conditioning of irradiated potatoes may reduce discolouration (Takehisa and Ito, 1986).

The content of sucrose and reducing sugars increased after irradiation but levels fall on storage to values similar to those observed in untreated potatoes. The suitability of tubers for processing into crisps and french fries was unaffected by irradiation and storage (Joshi *et al.*, 1990; Liu *et al.*, 1990). The sensory quality of potato chips made from irradiated potatoes may be improved (Khan *et al.*, 1986). Initially, *ascorbic acid* levels were lower in irradiated potatoes but as storage time increased, the *ascorbic acid* content was comparable or higher in irradiated tubers when compared with the control (Joshi *et al.*, 1990).

Chlorophyll formation is inhibited in irradiated tissues but not glycoalkaloid (solanine) synthesis (Patil *et al.*, 1971).

Detection

A promising method of identifying irradiated potatoes is the measurement of changes in *impedance*.

Potential application

Although irradiation is effective, it may not be an *economic* method of sprout inhibition in potatoes. The *economics* of irradiation of potatoes have been considered by Fiszer *et al.* (1985). Cost-benefit analyses of potato irradiation in a number of countries have been reported (IAEA, 1993).

Legal clearance for the irradiation of potatoes is given in many countries (see Table 10, page 86) and there have been a number of successful marketing trials (Thomas, 1983 and see Table 11, page 98). Commercial irradiation facilities to treat potatoes have been operational in Shihoro, Japan, since 1973 (Takehisa and Ito, 1986) (see Table 5, page 32).

See also Impedance and conductivity; Inhibition of sprouting; Legislation; Market trials.

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Poultry

Irradiation may be used to extend chilled shelf-life by reducing microbial populations and to eliminate pathogenic microorganisms such as *Salmonella*, *Campylobacter*, *Yersinia* and *Listeria*. Recommended doses are 1–2.5 kGy for the fresh product and 3–5 kGy for the frozen product.

Spoilage and pathogenic bacteria

Extensive research on the microbiology of irradiated chicken has been reviewed (Giddings and Marcotte, 1991; IAEA, 1993). In fresh poultry, *micro-organisms*, such as *Pseudomonas*, associated with spoilage of chicken at low temperatures, are destroyed by doses as low as 1 kGy. The pathogens, *Salmonella* and *Campylobacter*, *Listeria* and *Yersinia* are effectively eliminated by a dose of 2.5 kGy.

Freezing confers greater radiation resistance to *micro-organisms*. At −18°C, doses of 3–5 kGy are required to give substantial reductions in *micro-organisms* (see Table 13, page 104). Gram-negative organisms are more sensitive to *ionizing radiation* than Gram positive organisms and *yeasts* (see Table 14, page 104). Significant reductions in the numbers of pathogenic *bacteria*, including *Salmonella*, *Campylobacter*, *Yersinia*, *Escherichia coli*, *Staphylococcus* and *Listeria*, can be achieved in frozen poultry meat. These *micro-organisms* are associated with frozen mechanically separated chicken (MSM); 3 kGy is a typical dose for the treatment of frozen MSM (Sadat and Vassenaix, 1990).

There have been concerns that poultry irradiation would increase the potential hazard of radiation-resistant spores of pathogenic *bacteria*, particularly *Clostridium botulinum* (Firstenberg-Eden *et al.*, 1983). At a dose of 3 kGy, *Clostridium botulinum* type E did not compete with the surviving natural microflora of chicken skin, even under temperature abuse conditions. Spoilage off-odours in the irradiated product were observed prior to *toxin* formation.

Guidelines

- A Code of Good Irradiation Practice for Prepackaged Meat and Poultry Products (to control pathogens and/or extend shelf-life), ICGFI Document No. 4, International Atomic Energy Agency, Vienna (1991).
- F1356 – Guide for the Irradiation of Fresh and Frozen Red Meats and Poultry (to control pathogens). Annual Year Book of the American Society for Testing and Materials (ASTM) Standards, 15.07 (1993).

Treatment

Handling of poultry for irradiation treatment must conform to good manufacturing practice (IAEA, 1993). The meat must be stored at 4°C, or below, or in frozen conditions; these conditions should be maintained pre-irradiation, during irradiation and post-irradiation. Protection against recontamination of the product from microbial contamination and growth must be given, as with other forms of *meat* preservation.

Shelf-life extension of fresh poultry can be achieved by doses in the range 1–2.5 kGy, with the exact dose being determined by local conditions. In this range, the shelf-life of irradiated, chilled, chicken (0–4°C) can be increased 2- to 3-fold compared with untreated samples. The lower the dose the higher the quality of the product. Factors, including evisceration method, time of irradiation after slaughtering, *packaging* film, gaseous environment, *temperature* and type of cut, need to be taken into account (IAEA, 1993).

The radiation dose required for the inactivation of pathogenic *bacteria* in frozen poultry should be a minimum of 3 kGy.

Packaging and combination treatments

Irradiation combined with gas or vacuum packaging gives beneficial effects in extending shelf-life by suppressing aerobic spoilage *micro-organisms*. There is evidence to suggest that a vacuum, or a high carbon dioxide atmosphere, increases the sensitivity of *bacteria* on poultry meat to irradiation (Patterson, 1988). The practical benefits of irradiation and elevated carbon dioxide concentrations for shelf-life extension of chicken have been demonstrated (Grandison and Jennings, 1993).

Although the use of an *oxygen* impermeable barrier may inhibit *lipid* oxidation and discolouration during storage, this may compromise the microbiological safety of the product. The FDA ruling providing legal clearance for irradiation of poultry requires that the product must be packaged in materials that do not exclude *oxygen*. This limitation is needed to assure that conditions do not favour the growth of *Clostridium botulinum* before spoilage is evident (Pszczola, 1993).

Choice of *packaging* materials for irradiated poultry is hampered by a dearth of modern *packaging* materials specifically designed and approved for irradiated food. Polystyrene foam trays, which are commonly used for poultry, are not on the FDA list of approved *packaging* films (see Table 16, page 118). Use of these trays is permitted provided that they are laminated with one of the accepted film types, and provided the lamination functions as a barrier preventing migration of components from the trays to the food product (Rice, 1994). In France, MSM poultry is irradiated frozen, in 10 kg blocks, in polyethylene bags, by *electron beam* machines (Sadat and Vassenaix, 1990).

The combination of irradiation and mild cooking under vacuum (*sous vide*) is recommended for enhancing the shelf-life of chicken (Shamsuzzaman *et al*., 1992) but there are concerns about the possible growth and survival of *C. botulinum*.

Product characteristics

The minimum absorbed dose should be used to achieve the technological purpose and preserve the sensory quality of the product. A radiation dose of up to 2.5 kGy results in irradiated chilled poultry of acceptable organoleptic quality. Freezing prevents fat oxidation and *off-flavour* development. Radiation doses of up to 5 kGy can be tolerated by the frozen product (Gallien *et al*., 1983). Factors such as irradiation temperature, storage, and *packaging* film and atmosphere will influence results.

Flavour of poultry is less susceptible to change than odour or *colour*. The threshold for off-flavour *detection* in chicken is reported to a dose of 2.5 kGy, with *turkey* meat more sensitive to change (see Table 12, page 101). Method of cooking influences the perceived changes; frying, stewing or roasting will tend to disguise any *flavour* changes (Hannan and Shepherd, 1959).

An irradiation odour is apparent in irradiated raw chicken treated at doses of 2.5 kGy and below. The odour appears to dissipate on storage, cooking and with the use of *oxygen* permeable *packaging* (Kahan and Howker, 1978; Heath *et al*., 1990). Changes in *colour* are reported; irradiated chicken is described as 'pinker' than untreated samples (Kahan and Howker, 1978). This change is less obvious in dark meat and on cooking. The 'pink' appearance and off-odour of irradiated chicken is affected by the permeability of *packaging* film and contact time (Hannan and Shepherd, 1959).

Detection methods

A number of methods of detecting irradiated chicken meat have been investigated (IAEA, 1993). Electron spin resonance is the *detection* method of choice for irradiated poultry containing bone. The presence of *2-dodecylcyclobutanone* has been proposed as another potential indicator of irradiated poultry.

Nutrition

The effects of irradiation on the nutritional value of irradiated chicken have been reviewed in IAEA (1993).

The effects of radiation doses up 7 kGy on vitamins *cyanocobalamin*, *pyridoxine*, *niacin*, *riboflavin* and *thiamine* in chicken have been reported (Fox *et al*., 1989). *Thiamine* is known to be the most radiation sensitive of these vitamins. In cooked chicken breasts, treated with doses of 1 and 3 kGy, losses were 1.3 and 8.4%. Negligible losses of *tocopherol*, *thiamine* and *pyridoxine*, in frozen chicken irradiated at 2.5 kGy, have been reported (Gallein *et al*., 1985).

In reviewing available data to determine whether irradiation of poultry would have an adverse effect on the nutritional value of food, the FDA concluded that irradiation, at approximately 3 kGy, would not have an adverse effect on the nutritional value of a person's diet (FDA, 1990).

Potential application

The cost-benefits of irradiating poultry to improve product safety and increase shelf-life are widely recognized (IAEA, 1993). Public health benefits of irradiating poultry to prevent food-borne illness are considered to exceed irradiation costs (Giddings and Marcotte 1991; Todd, 1993). The *economic* feasibility of on-line irradiation in a poultry processing facility has been considered (Lapidot *et al*., 1993).

Legal clearance for the irradiation of chicken is given in many countries (Table 10, page 86). Commercial use of irradiation for MSM has taken place, in France, for several years (Table 5, page 32). The product is used in fine emulsions in sausages, stuffings and meat pies (Sadat and Vassenaix, 1990). In 1992, legal clearance for the irradiation of fresh poultry, frozen poultry and MSM was given in the USA. Fresh poultry treated at doses 1.5–3.0 kGy, to control *Salmonella* and other pathogenic *bacteria*, was successfully marketed in Chicago and Florida (Pszcola, 1993).

See also Clostridium botulinum; Combination treatment; D-values; Detection; Micro-organisms – relative resistances; Micro-organisms – safety; Nutrition; Salmonella; Turkey.

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Prawns *see* Shrimps and prawns.

Predictive modelling *see* Modelling.

Prions *see* BSE.

Proteins

General

The effects of *ionizing radiation* on proteins have been investigated for two distinct reasons. Firstly, to determine whether irradiation leads to any significant loss in nutritive value and secondly, to determine how irradiation interferes with the activity of those enzymes that contribute to the quality loss of some stored foodstuffs (Diehl, 1990).

Chemical effects on proteins

Since all proteins consist of peptide-bonded chains of amino acids, the effect of radiation on amino acids is the most important consideration influencing the effect of radiation on proteins. Major reactions involve decarboxylation and oxidative (if oxygen is present) or reductive (if anaerobic) deamination. The yields of reaction products at doses relevant to the processing of foods are low. For example, 10 kGy irradiation of a solution of free alanine generated products per kilogram of amino acid as follows: pyruvic acid, 176 mg; propionic acid, 80 g; ammonia, 79 mg; carbon dioxide, 27 mg; acetaldehyde, 27 mg; ethylamine, 8 mg; hydrogen, 2.3 mg (Liebster and Kopoldova, 1964). The sulphur amino acids such as cysteine, cystine and methionine may act as *free radical*-scavengers, thus ameliorating the degradative effects on other of the amino acid components of proteins. However, their breakdown also generates end products such as hydrogen sulphide, which have undesirable sensory effects.

Products of the radiolysis of water react with aromatic amino acids principally to hydroxylate the aromatic ring. For example, o-, m- and p-tyrosines are formed from phenylalanine. The presence of *o-tyrosine* has been proposed as one method for the *detection* of irradiated foods (Swallow, 1977; Urbain, 1977).

Structural effects may result from such amino acid reactions, but also from chain scission at the peptide bond, leading to changes in the viscosity of protein solutions, aggregation, etc. With over 20 amino acids, the total range of possible reaction products is therefore great, but the quantitative effect on proteins in foods during irradiation is, of course, small.

Physicochemical and organoleptic characteristics of proteins are not appreciably affected at doses suitable for microbial decontamination. There is legal clearance in France for animal blood, plasma and cruor to be irradiated up to 10 kGy and for caseins and caseinates up to 6 kGy (see Table 10, page 86).

Nutritional effects on proteins

Many studies of the nutritional effects of irradiation on proteins have been made with generally only small or insignificant changes found. For example, irradiation of fish and meat meal, *eggs*, *wheat* and wheat gluten (Kennedy and Ley, 1971) showed little change in nutritive value in feeding studies after irradiation at doses up to 10 kGy. The biggest changes were in wheat gluten (7%). At 50 kGy larger losses occurred, but were largely reversed by supplementation of the diets with methionine.

Enzyme inactivation

In addition to the specific amino acid reactions, radiation causes changes in the secondary and tertiary structure of proteins, but the quantitative effects in foods are very small. Consequently, enzyme inactivation is not a major outcome of food irradiation. On the contrary, particularly for long-ambient stored, radiation-sterilized foods, some other means of enzyme-inactivation, most commonly heat, must be employed. As an example, Rhodes and Meenungwan (1962) determined the doses necessary to reduce various enzymatic activities on lamb's liver. Whilst protease activity fell by about 20% after a dose of 10 kGy, lipase and phospholipase activities required doses of 80 to 100 kGy before any inactivation was detected at all. With many plant tissues, whilst total enzyme levels may hardly change on irradiation, their *in vivo* activities may nevertheless actually increase as a result of release, or diffusion, through 'leaky' membranes to more easily reach their hitherto unavailable substrates. For example, browning can be exacerbated by the action of polyphenol oxidases.

See also Colour; Enzymes; Sterilization.

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Protozoa *see* Parasites.

Prunes *see* Dried fruit.

Pseudomonas

General

Pseudomonads are Gram-negative oxygen-dependent rod-shaped *bacteria*, which typically grow rapidly on *meat* and other protein-rich, high-pH, high-water activity foods including cut *vegetables* stored in air. Many *Pseudomonas* species, and related oxidative Gram-negative *bacteria*, are psychrotrophic and so spoil chill-stored foods. Their inhibition (e.g. by vacuum packaging, by modified atmosphere packaging in atmospheres enriched with carbon dioxide, or by inhibitory levels of salt in cured products) or their inactivation (e.g. by low doses of radiation), usually results in slower, less objectionable spoilage by lactic acid bacteria.

Table 18 D_{10} values of bacteria irradiated in chicken mince under various atmospheres (Patterson, 1988).

Isolate	Atmosphere			
	Air	CO_2	Vacuum	N_2
Lactobacillus spp.	0.593	0.400	0.502	0.510
Moraxella phenylpyruvica	0.858	0.676	0.625	0.880
Escherichia coli				
Nutrient agar	0.388	0.296	0.266	0.255
MacConkey agar	0.351	0.288	0.271	0.233
Salmonella typhimurium				
Nutrient agar	0.502	0.540	–	0.622
Brilliant Green agar	0.436	0.442	–	0.550
Enterococcus faecalis	0.651	0.702	0.697	0.679
Staphyloccus aureus	0.419	0.411	0.398	0.371
Pseudomonas putida	0.080	0.110	0.060	0.081

Radiation resistance

Most of the important spoilage *Pseudomonas* species, such as *P. fragi*, *P. fluorescens* and *P. putida*, have exceptionally low radiation resistances, and so are the first to disappear in low dose irradiated foods. For example, *D-values* of *P. putida* ranged from only 0.06 kGy, in vacuum, to 0.11 kGy, in carbon dioxide packed chicken (Patterson, 1988, and see Table 18).

See also Lactobacillus.

Reference

Patterson, M. (1988) Sensitivity of bacteria to irradiation on poultry meat under various atmospheres, *Letters in Applied Microbiology*, **7**, 55–8.

Pteroylglutamic acid *see* Folic acid.

Pulses *see* Legume.

Pyridoxine (vitamin B6)

General

Major dietary sources of pyridoxine include red *meats*, *poultry*, *cereal grains*, *nuts* and some *pulses*. Vitamin B6 occurs in a number of biologically active forms. In pyridoxal, the alcohol group of pyridoxine ('pyridoxol') is replaced by an aldehyde group and in pyridoxamine by a methyleneamine group. *In vivo*, vitamin B6 contributes the coenzymes pyridoxal phosphate and pyridoxamine phosphate, which are involved in a wide range of reactions involving amino and carboxyl group transfers. Deficiency leads to nerve damage and related symptoms, wasting and anaemia.

Radiation sensitivity

In general, radiation-induced losses of pyridoxine in foods have been found to be small, similar or slightly greater than losses of *thiamine*. Losses induced by radiation *sterilization* of *poultry* and liver, at doses up to 55 kGy, were less than those induced by sterilization by heat (Richardson *et al.*, 1961). The converse was true for *cabbage*. Most studies have found little pyridoxine loss in foods irradiated at realistic doses and little further loss on subsequent storage.

See also Vitamins.

Reference

Richardson, L.R., Wilkes, S. and Ritchey, S.J. (1961) Comparative Vitamin B6 activity in frozen, irradiated and heat-processed foods, *Journal of Nutrition*, **73**, 363–8.

Q

Quality improvement *see* Legume; Juice; Vegetables – dried.

Quarantine *see* Insect disinfestation.

Queensland fruit fly ***(Bactrocera tryoni)*** *see* Insects.

R

Rad
The rad is an old unit of radiation absorbed dose, now replaced by the *gray* (Gy). The rad is defined as the absorption of 100 ergs of energy per gram of matter.

1 Gy = 100 rad

Radappertization
A term used to describe treatment of food with high radiation doses. The doses need to be sufficiently great to kill all *micro-organisms* of food spoilage or public health significance (*viruses* excepted). Doses need to be greater than 10 kGy (25–45 kGy may be required). Radappertization is analogous to commercial sterility.

See also Sterilization.

Radicidation
A term used to describe treatment of food with radiation doses necessary to kill non-sporeforming microbial pathogens. Doses are generally below 10 kGy (2–8 kGy range). The term may also be applied to *parasites*, in which case the required dose is in the range 0.1–1 kGy.

See also Micro-organisms – relative resistances.

Radioactivity
There are a number of naturally radioactive substances, e.g. uranium, radium. Other elements can be made radioactive by bombarding them with particles emitted by radioactive atoms, e.g. radioactive cobalt-60 is manufactured from stable metal cobalt-59.

Radioactivity is the spontaneous transformation of an unstable nucleus into a more stable form, usually accompanied by the emission of a charged particle. As a result of these spontaneous nuclear disintegrations, *ionizing radiation* is emitted. The unit of radioactivity is the *becquerel*, which equals one disintegration per second.

See also Induced radioactivity; Radionuclide.

Radioisotope *see* Radionuclide.

Radiolytic product
The product produced by chemical decomposition induced by *ionizing radiation*. Radiolysis is chemical decomposition caused by irradiation.

See also Unique radiolytic products.

Radionuclide
Naturally occurring and man-made radionuclides are nuclides (isotopes of an element) that are unstable and undergo natural radioactive decay. The term radioisotope is commonly used. The time taken by a radionuclide to decay to half the original level of *radioactivity* is known as its *half-life*. This is specific for each radionuclide.

The radionuclides cobalt-60 (^{60}Co) or caesium-137 (^{137}Cs) emit *gamma rays* that can be used to treat food (ACINF, 1986; WHO, 1994). Cobalt-60 is produced from stable metal cobalt-59 (^{59}Co), by exposure of ^{59}Co to neutrons in a nuclear reactor for about a year. Cobalt-60 has a *half-life* of 5.3 years and emits *gamma rays* of energy of 1.17 and 1.33 MeV. Caesium-137 is formed in nuclear reactors as a result of the fission of uranium isotopes; it may be extracted as a by-product of reprocessing spent fuel elements. Caesium-137 has a *half-life* of 30.1 years and emits *gamma rays* of energy 0.66 MeV.

For food irradiation, ^{60}Co is used in preference to ^{137}Cs because it is more readily available and safer to use. Cobalt-60 is used for cancer treatment and is commonly used for the sterilization of medical products, such as syringes, dressings, and pharmaceutical and cosmetic products. The supply of ^{60}Co is limited and it is considered that, if a modest level of commercialization of food irradiation took place world-wide, there could be insufficient (Lagunas-Solar, 1995).

In order to maintain a constant throughput capacity in a ^{60}Co irradiation plant, an addition of about 12% of the original source activity of ^{60}Co per year is needed. A comparison of radionuclide irradiators and electron accelerators is presented in Table 9, page 52.

See also Radioactivity; Facilities.

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Radura symbol *see* Labelling.

Radurization

A term used to describe treatment of food with *ionizing radiation* to reduce populations of *micro-organisms*, in order to delay onset of spoilage. Doses used are generally below 10 kGy. Radurization enhances keeping quality usually at refrigeration temperatures. Radurization is analogous to pasteurization.

See also Micro-organisms – relative resistances.

Raisin *see* Dried fruit.

Rambutan (*Nephelium lappaceum*)

The rambutan is a tropical *fruit*, closely related to the *lychee* and *longan*, which is grown in Australia, Malaya and Indonesia. Irradiation has been used to increase the shelf-life of the rambutan, by delaying fungal spoilage (Thomas, 1988). Approximately 1 kGy appears to be the optimal dose, although there may be varietal differences. *Insect disinfestation* could be achieved at this dose level.

Reference

Thomas, P. (1988) Radiation preservation of foods of plant origin, Part VI, Mushrooms, tomatoes, minor fruits and vegetables, dried fruits, and nuts, *CRC Critical Reviews in Food Science and Nutrition*, **26**(4), 313–58.

Raspberry *see* Berry.

Ready meals

Ready-to-eat foods are commonly used in hospitals and other institutions, commercial airlines, as well as in the retail market. There is potential application for irradiation to control bacterial pathogens in ready meals (Todd, 1993).

The effect of irradiation on ready meals will depend on the sensitivity of the individual components. In a study of meals irradiated at 1 or 2 kGy (Kilcast, 1991), the limiting factors were *off-flavour* and textural changes. The meals that were reheated and served hot, and items with stronger *flavours*, were least affected. At 1 kGy, butter was rancid, iceberg *lettuce* lost crispness and green beans were soft. At 1 kGy, a microbiological advantage in terms of levels of pathogenic *bacteria* was achieved. Low radiation doses and careful selection of meal components are recommended when treating ready meals.

The potential use of a *combination treatment* of heat and low dose irradiation for prepared meals, containing *meat*, gravy, vegetables, *fish* and *dairy products*, has been demonstrated (Report, 1993).

See also Sterilization.

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Regulations *see* Legislation.

Re-irradiation

Re-irradiation of foods is prohibited by the Codex General Standard for Irradiated Food. An exception is given for foods with low moisture content, e.g. *cereal grains*, *pulses* and dehydrated food, which can be re-irradiated for the purpose of *insect disinfestation*.

See also Codes of practice.

Rem

The rem (roentgen equivalent mammal) is an old term used to describe the dose absorbed by a mammal when exposed to *ionizing radiation*, which is biologically equivalent to the dose of 1 *roentgen* of *gamma radiation*.

The rem has been replaced by the *sievert* (1 sievert = 100 rem).

Reovirus *see* Viruses.

Rep

The rep (roentgen equivalent physical) is an old term used to describe the dose delivered by 1 *roentgen* to 1 gram of water. It was the unit of absorbed dose of any *ionizing radiation* with a magnitude of 93 erg/g (0.93 rad).

The rep was superseded by the *rad* and subsequently by the *gray* (1 Gy = 100 rad).

Retinol (vitamin A)

General

Dietary sources of vitamin A (retinol, $C_{20}H_{29}OH$) include most animal foods, particularly liver, kidney, egg yolks, *milk* and butter, and *fish*. Ingestion of carotenes, widely distributed in plants, leads to the generation of vitamin A *in vivo* so that *fruits* and *vegetables*, such as *carrots*, spinach and *oranges*, are good sources too. Of the two forms of vitamin A that are present in animals, A1, containing one less double bond than A2, has twice its biological activity. The plant carotenes are molecules of about twice the size of retinol. Intestinal enzymes generate two molecules of retinol from each ingested β-carotene molecule.

Radiation sensitivity

Dry retinol and dietary precursors, such as β-carotene, are relatively radiation-tolerant, with little inactivation brought about by doses up to about 20 kGy (Lukton and MacKinney, 1956). However, losses reported for foods given practical doses are small. Even doses as high as 200 kGy only reduced β-carotene levels in *tomatoes* by about 10 to 20% (Lukton and MacKinney, 1956), depending on whether or not *oxygen* was present. Irradiation of *carrot* puree at 20 kGy caused no more than a 5% loss. Changes in vitamin A activity in *fruits* given low doses for disinfestation or to delay *ripening* were well below this level of loss, e.g. mangoes (Thomas and Janave, 1965); *papayas* and *strawberries* (Beyers *et al.*, 1979).

See also Vitamins.

References

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Rhizopus *see* Moulds.

Riboflavin (vitamin B2)

General

Riboflavin occurs in nutritionally significant amounts in many foods. Major sources are *meats*, particularly liver, yeast and yeast products, *milk*, green *vegetables* and *fruits*, *pulses*, *nuts* and *cereal grains*.

The molecule is amongst the most chemically stable of the vitamins. The biologically active forms of riboflavin are the flavin nucleotides FMN (flavin mononucleotide) and FAD (flavin adenine dinucleotide), which are key co-factors in the electron transport chain. Vitamin B2 deficiency therefore causes a wide variety of symptoms including interference with neurological and circulatory functions, and depression of growth.

Radiation sensitivity

As a consequence of its relative chemical inertness, riboflavin is the vitamin most resistant to irradiation in most foodstuffs. Sometimes levels of riboflavin in foods have even been found to rise following irradiation, most probably due to release from binding to *proteins*, e.g. in *pork* meat (Fox *et al.*, 1989) and *onions* (Le Clerk, 1963).

See also Vitamins.

References

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Rice (*Oryza sativa*)

Irradiation could be used for insect disinfestation and for microbial decontamination.

Insect disinfestation

Doses up to 1 kGy have been recommended by the Joint FAO/IAEA/WHO Expert Committee (1981) for the irradiation of rice, for the purposes of *insect disinfestation*. Doses of the order of 0.5 kGy were needed to control rice pests, such as the rice weevil (*Sitophilus oryzae*), the red flour beetle (*Tribolium castaneum*), the sawtoothed grain beetle (*Oryzaephilus surinamensis*) and the flour moth (*Ephestia kuehniella*) (El Kady, 1981). In general, at these low radiation doses, the physicochemical and sensory properties of rice are unaffected.

Microbial decontamination

Mould damage is a cause of *post-harvest losses* in rice that is not handled according to good manufacturing practice. Radiation doses, in excess of 1 kGy, are required for microbial control (Lorenz, 1975). The possibility of using irradiation as an alternative to the use of fungicides has been investigated, but is not recommended.

At doses above 1 kGy, there is evidence that irradiation influences cooking quality, sensory properties and the physicochemical characteristics of rice, depending on a number of factors, including rice variety, moisture content and storage time. Reduced cooking time, increased water uptake and increased amount of *starch* in residual cooking liquid are reported (Sabularse *et al.*, 1991). An increase in yellowness and the presence of *off-flavours* was found in Australian rice (Wootton *et al.*, 1988). No effect on *niacin* and *thiamine* was recorded at this level in Pakistani rice (Tape and Ferguson, 1966). The threshold level for damage may be higher in Taiwan-produced rice grains (Wang *et al.*, 1983).

Damage to *starch* in rice grains is evident above 1 kGy (Mahmoud *et al.*, 1989). In addition, *starch* pasting properties, gelatinization time, viscosity, soluble amylose content and percentage of damaged *starch* grains were affected.

See also Cereal grains; Legislation; Insect disinfestation; Moulds; Starch.

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Ripening and senescence

A delay in ripening or senescence of fresh *fruits* and *vegetables* can extend the shelf-life of produce and reduce spoilage losses. This occurs in certain *fruits* and *vegetables* when exposed to low doses of *ionizing radiation*, and depends on a number of factors including *fruit* species, cultivar, stage of maturity at time of treatment, time of irradiation after harvest, and storage conditions.

A delay in post-harvest ripening can occur only in climacteric *fruit* (Akamine and Moy, 1983). Senescence, or physiological breakdown, may be delayed in both climacteric and non-climacteric *fruit* during post-harvest storage.

Climacteric fruits and vegetables

Fruits and *vegetables* are classed as climacteric and non-climacteric. Climacteric *fruits* are those which ripen post-harvest, and undergo marked increases in respiration and production of ethylene (Rosenthal, 1992; Salunkhe *et al.*, 1991). Typical characteristics of ripening are a change in pigmentation, softening of *texture*, and increases in sweetness and decreases in astringency.

Non-climacteric *fruits* reach a desirable ripeness on the tree and do not undergo rapid metabolic changes after harvesting. Maturity is regulated by storage. Ripening may be stimulated in these types of *fruits*, possibly due to radiation-induced generation of ethylene.

Classification of some fruits and vegetables is as follows (Salunkhe *et al.*, 1991):

Climacteric	**Non-climacteric**
apple	cherry
apricot	cucumber
avocado	fig
banana	grape
mango	grapefruit
papaya	lemon
peach	melon
pear	orange
plum	pineapple
sapota	strawberry
tomato	

Most leafy *vegetables* are classified as non-climacteric.

If *fruits* are irradiated before the onset of the climacteric period, inhibition of ripening may be pronounced (although, in the case of *peaches* and *nectarines*, ripening is accelerated). An undesirable consequence may be uneven ripening of the *fruits*. Once the ripening process has been initiated, irradiation has little effect.

See also Fruits and vegetables.

References

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Roentgen

The roentgen is the original unit of measurement of radiation defined in terms of *ionization* events. 'Roentgen equivalent physical' (*rep*) and 'roentgen equivalent mammal' (*rem*) are the old units of dose. The roentgen is superseded by the *gray* (Gy).

S

Safety of irradiated food

The safety of irradiated food has been established from a toxicological, nutritional and microbiological standpoint (WHO, 1984).

See also Induced radioactivity; Micro-organisms – safety; Nutrition; Polyploidy; Toxicology.

Reference

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Safety of irradiation facilities

A number of controls ensure the health and safety of personnel in irradiation facilities and, in addition, protect the general public, e.g. from environmental contamination by a *radionuclide* source. Safety measures in plant operation are considered in detail in ICGFI (1992).

Under normal operating conditions, all radiation exposures are prevented because the radiation source is shielded. Biological shielding in the form of thick concrete walls is provided to house either a *cobalt-60* source or an *electron beam* machine. The walls of the irradiation chamber, and maze, through which access is made to the source, are constructed from concrete, 1.5 metres thick. In addition, a deep pool of water (approximately 7 metres deep) is used for storage of a *cobalt-60* source when not in use, or for manipulation during source replenishment, to prevent worker and environmental exposure. *Electron beam* machines can be turned off when not in use, when personnel need to enter the cell to load the product, and for servicing and maintenance.

Irradiation facilities are designed with several levels of protection in place to detect equipment malfunction and prevent personnel from accidental exposure. Potentially hazardous areas are monitored and a system of interlocks prevents unauthorized entry into a radiation cell when the source is exposed. Worker safety also relies on strict operating procedures and proper training. All workers are continuously monitored for radiation exposure with personal dosimeters.

All radiation plants must be licensed. Facilities are subject to inspection and control by regulatory authorities, in order to make certain that the relevant national and international radiological safety standards are being achieved and maintained. In the UK, regulations governing the safety of radiation installations and the transport of *radionuclides* are stated in the Ionising Radiation Regulations 1985.

Guidelines

- A code of practice provides practical guidance concerning the UK Ionising Radiation Regulations 1985: The protection of persons against ionising radiation arising from any work activity, HMSO, London (1985).
- A list of IAEA publications relating to radiological protection and safe transport of radioactive sources is found in: Guidelines for Preparing Regulations for the Control of Food Irradiation Facilities, ICGFI Document No. 1., International Atomic Energy Agency, Vienna (1991).
- Radiation Safety of Gamma and Electron Irradiation Facilities, IAEA Safety Series, STI/PUB/896, is published by the International Atomic Energy Agency, Vienna (1992).

See also Facilities; Sievert.

Reference

ICGFI (1992) *Training Manual on Operation of Food Irradiation Facilities*, International Consultative Group on Food Irradiation, ICGFI Document No. 14, Vienna, pp. 85–91.

Salmonella

General

Salmonellae are Gram-negative non-sporing rod-shaped *bacteria*. Well over 2000 distinct serotypes are known.

Whilst many are capable of slow growth at temperatures as low as about 5°C, they are note specially tolerant of low water activity (e.g. high levels of salts or sugars in foods) or low pH values. They gain access to foods predominantly by contamination from the enteric contents of animals and especially from *poultry*

Thousands, or even tens of millions, of cells of most *Salmonella* serotypes are required to be ingested in order to cause infection. However, much smaller numbers may be infective in some circumstances, e.g. depending on the type of food, the particular serotype and the susceptibility of the individual. For example, it was estimated that ingestion of only about 50 cells of *S. napoli* in contaminated chocolate was sufficient to cause disease. *S. dublin* is more virulent than most other serotypes. *S. typhi*, though more often water- than foodborne is, of course, much more highly infective. The very young, very old and the immunocompromised are more susceptible to salmonellae infection than are healthy adults.

Radiation resistance

The radiation resistance of salmonellae depends on the nature of the food, the packaging atmosphere, temperature, etc., but generally *D-values* are between 0.4 and 0.6 kGy. For example, *D-values* for *S. typhimurium* irradiated at 10°C, in minced chicken, ranged from about 0.5 kGy in air, to 0.54 in carbon dioxide, and to 0.62 in a vacuum (Patterson, 1988, and see Table 18, page 131). *S. typhimurium* had a *D-value* of about 0.4 kGy, and *S. enteritidis* a *D-value* of about 0.58 kGy, irradiated in chicken at 2°C (Thayer *et al.*, 1990).

Irradiation of *poultry*, and other foods, to eradicate salmonellae will also inactivate other, non-pathogenic, enterobacteria and other radiation-sensitive *micro-organisms*, and thereby bring about major changes in the microbial flora of the food. For example, 2 and 4 kGy irradiation of frozen chicken (Prachasitthisakdi *et al.*, 1984) caused a satisfactorily large reduction in the numbers of Gram-negative rods, but much less reduction in the numbers of Gram-positive cocci. *Micrococcus* species and *yeasts* became predominant in the psychrotrophic flora, whilst *Streptococcus* and *Micrococcus* species predominated amongst the mesophiles. Overall, this was not expected to introduce any new, alternative hazard. Likewise, Wongchinda *et al.* (1985) and Mossel and Stegeman (1985) studied the microflora of thawed and temperature-abused *shrimps* that had been irradiated frozen. They found similar shifts from Gram-negative to Gram-positive flora but concluded that the shift in flora caused by irradiation did not introduce new microbiological hazards.

Cost benefits of Salmonella radicidation of poultry

Whilst it is difficult to accurately forecast the *economic* benefits that would accrue from the elimination of salmonellae from *poultry*, as opposed to the less easily quantified benefit of relief of suffering, several attempts have been made (Todd, 1993).

A particularly careful study was undertaken by Yule *et al.* (1986), who evaluated the cost of a hospital outbreak of poultry-borne salmonellosis, then extrapolated from their data to estimate the total cost of poultry-borne salmonellosis in Scotland. This was compared with the costs of irradiating *poultry* as a salmonellae control measure. It was concluded that the public health benefits exceeded the cost of the irradiation. The additional removal of other pathogens from the *poultry* was not included in the analysis.

See also Micro-organisms – safety.

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Sapota (*Achras zapota*); Sapodilla

The sapota or sapodilla is widely grown in Central America, the West Indies and the Phillipines; it is a *fruit* of the climacteric class. Contradictory results have been obtained on the effect of irradiation on sapotas (Thomas, 1988). A delay in *ripening* and an increase in shelf-life may result from treatment with doses of 0.1 kGy.

See also Ripening and senescence.

Reference

Thomas, P. (1988) Radiation preservation of foods of plant origin, Part VI. Mushrooms, tomatoes, minor fruits and vegetables, dried fruits and nuts, *CRC Critical Reviews in Food Science and Nutrition*, **26**(4), 313–58.

Sausage *see* Meat.

Seafood

Molluscs: clams, oysters, scallops, mussels.
Crustaceans: crabs, lobsters, shrimps and prawns.

(Irradiation of shrimps and prawns is described under a separate heading, Shrimps and prawns.)

For the inactivation of parasites and for a reduction in numbers of *micro-organisms*, including pathogens, leading to an extension of refrigerated shelf-life and improvement in product safety, the recommended dose is 0.5–2.2 kGy.

Treatment

Raw or poorly cooked molluscs and crustaceans can be sources of the parasite *Angiostrongylus* and *Paragonimus* spp. Irradiation has been considered as a method of controlling these *parasites* (see Table 17, page 121), although the use of effective doses may result in adverse sensory changes in the product.

The effect of irradiation on molluscs and crustaceans has been reviewed by Nickerson *et al.* (1983). Doses of the order of 1–2 kGy have been used to extend the shelf-life of clam meat, scallops and oysters. There is particular interest in the use of irradiation to guarantee the safety of these products. At optimal dose levels, there is little effect on the *texture* or appearance of mollusc meats. Excess doses result in *off-flavours* and off-odours, or loss of typical flavour. In scallops, a naturally occurring garlic-like *off-flavour* was reduced in intensity by irradiation treatment (Poole *et al.*, 1990).

Similar results are obtained for the irradiation of crustacea. Cooked crab meats could be treated with radiation doses of the order of 2 kGy, and cooked lobster meat with 0.75–1 kGy, to extend refrigerated shelf-life. Radiation causes melanosis in Norway lobster (scampi). Blanching for 2 minutes (to inhibit melanosis), irradiation at 2–3 kGy and storage at 0–1°C gave a significant shelf-life extension and preserved the quality of the product (Hannesson and Dagbjartsson, 1971). Spice treatment has been used to inhibit radiation-induced melanosis (Nickerson *et al.*, 1983).

It is recommended that *packaging* materials for irradiated products should be impervious to moisture and *oxygen*, and that temperatures as near 0°C as possible, without freezing, should be maintained during treatment and storage (Nickerson *et al.*, 1983). Irradiated seafoods may be sensitive to off-odour transmission from certain plastic packaging films (Tinker *et al.*, 1966).

Detection

ESR is the recommended method of detecting irradiated crustaceans.

Potential application

Cleansing techniques (depuration) are traditionally used to decontaminate shellfish harvested from potentially contaminated seawater. With the aim of developing an irradiation-depuration process for shellfish, the radiation resistance of *Esherichia coli*, *Salmonella typhimurium*, *Shigella flexneri*, *Streptococcus faecilis*, in clams and mussels, has been established (Licciardello *et al.*, 1989).

There is public concern over the presence of Vibrio *bacteria* in oysters harvested in the Gulf of Mexico. This has resulted in a drop in sales and consumption of both raw and cooked shellfish in this area. The use of irradiation as a processing technology to eliminate species of Vibrio *bacteria* from live or processed oysters is economically feasible (Kilgen, 1993; Mallet, 1991). There is pressure on the FDA to give legal clearance for irradiation of shellfish up to 1 kGy.

See also ESR; Fish; Legislation; Parasites; Shrimps and prawns; Vibrio.

References

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Seasonings *see* Spices.

Sensitizers

Many compounds decrease the apparent radiation resistance of vegetative and spore forms of *micro-*

organisms and other living things. These include such simple substances as sodium chloride, iodoacetic acid, iodoacetamide, iodate, iodide, vitamin K5 and many others (Dean and Alexander, 1962, Matsuyama *et al.*, 1960). There have been investigations into the possibility of adding some of these substances to foods, in order to reduce the doses of radiation needed to obtain a particular desired effect. However, it has usually been found that whilst some of these 'sensitizers' may show substantial effects *in vitro* (e.g. in laboratory experiments in which *micro-organisms* are suspended in water, buffers or dilute media), their effects are greatly reduced when tested for in real foods.

The reduction in the effectiveness of such sensitizers in real foods probably results because they mostly act via the production of short-lived intermediates, which are produced by reaction of the sensitizer molecule with the radiolysis products of water. These short-lived products (e.g. uncharged iodine *free radicals* derived from iodide), whilst being highly microbicidal, and therefore 'radiation synergists' in water, react so readily with the major components of real foodstuffs that they quickly become 'quenched', i.e. unavailable for reaction with the *micro-organisms* that the food contains. The extent of sensitization that can be achieved is sometimes substantial, but the quenching by organic matter is likewise substantial (see Figure 12), so that the procedures have not found deliberate use in food processing.

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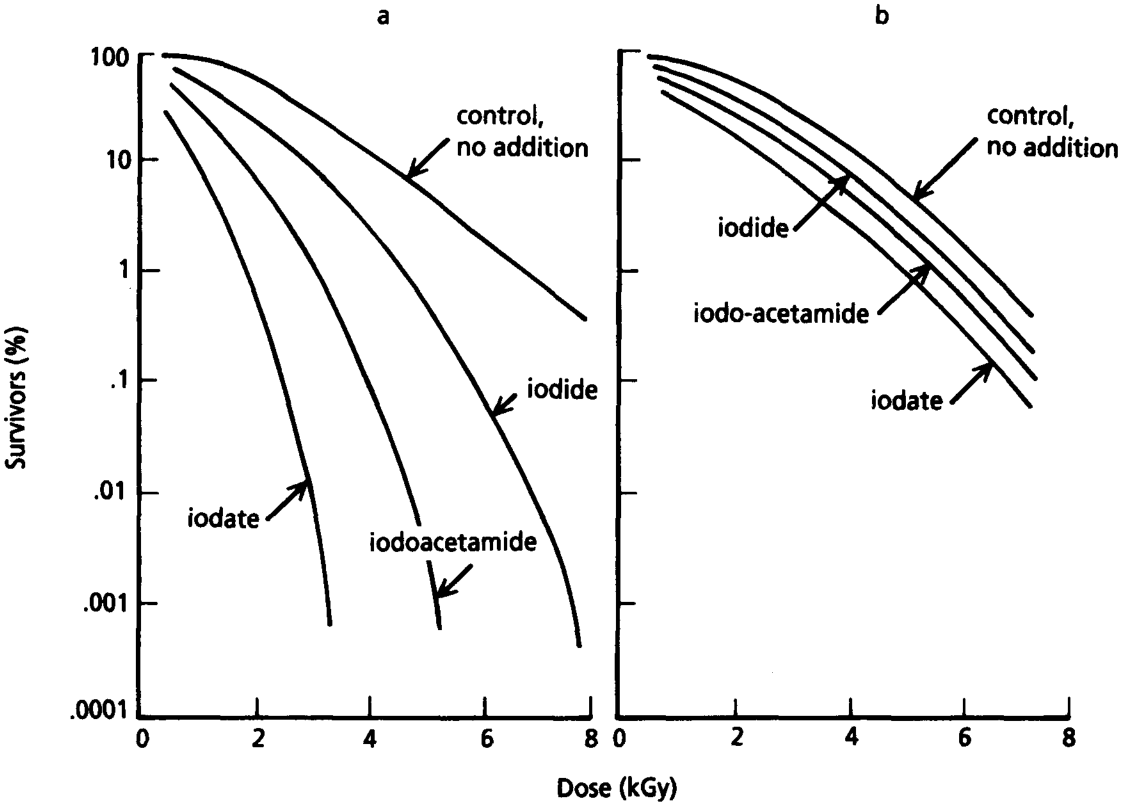

Figure 12 Enhancement of the radiation sensitivity of spores of *Bacillus cereus* by various iodine containing 'sensitizers' when irradiated in water (a) and the contrasting suppression of sensitization when the suspending medium was heat infusion broth (b). Sensitizer concentrations were 1 mM (from Gould, 1970).

Sensory evaluation

Sensory evaluation of irradiated foods does not involve special methods of assessment. Methods of assessing the sensory characteristics of food, with special reference to irradiated foods, are summarized in Anon (1982). Since the treatment can result in the formation of off-flavours, methods highlighted as specific for the detection of off-flavours and taints (Kilcast, 1993) may be appropriate.

See also Colour; Flavour; Texture.

References

Anon (1982) *Training Manual on Food Irradiation Technology and Techniques*, International Atomic Energy Agency, Vienna, pp. 64–9.

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Shallot *see* Onion.

Shellfish *see* Seafood; Shrimps and prawns.

Shelf-life extension *see* Applications.

Shielding *see* Facilities; Safety.

Shigella

General

The genus *Shigella* is part of the family Enterobacteriaceae. The cells are Gram-negative, rod-shaped and non-motile. Four species within the genus fall into four distinct serological groups: *S. dysenteriae* (serogroup A), *S. flexneri* (serogroup B), *S. boydii* (serogroup C), and *S. sonnei* (serogroup D).

Shigella cause the disease dysentery, commonly called 'bacillary dysentery' or 'shigellosis'. Most cases are caused by *S. sonnei*. *S. dysenteriae* has a much higher fatality rate than other species, but is responsible for a much smaller number of cases. The organisms are very infectious. As few as 10 cells of *S. dysenteriae*, and 100–10^4 cells of the other species, given to healthy volunteers caused disease (Doyle, 1990).

Shigella is generally water-borne and spread from person to person by poor hygiene. It is not surprising, therefore, that dysentery caused by *Shigella* species is responsible for much of the morbidity and mortality in those developing countries in which sanitary conditions remain primitive. However, shigellae do contaminate foods, e.g. through contaminated water or from infected food handlers. Contamination of *fish* and *shellfish*, particularly those that may be consumed raw or without reheating, is a particular problem.

Radiation resistance

Although the radiation resistances of shigellae in susceptible types of foods, such as oysters, crab meat, *shrimps* and salmon, were higher than in laboratory media, *D-values* in the foods were lower than those of salmonellae, ranging from about 0.25 to 0.4 kGy (Quinn, *et al.*, 1967; Anderson, 1969). Thus doses of 5 to 8 kGy, commonly recommended for these foods, will very effectively eliminate those pathogens.

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Shrimps and prawns

- Crangonidae (European species)
- Penaeidae (tropical species)
- Pandalidae (deep-sea species of Pacific or Icelandic waters)

For extension of shelf-life and improvement in product safety, the recommended dose is 1–2 kGy for chilled products and 4–5 kGy for frozen products.

Spoilage and pathogenic bacteria

Extensive work on the microbiology, sensory qualities and shelf-life of irradiated shrimps and prawns has been reviewed by Vyncke (1973) and Nickerson *et al.* (1983). The total bacterial count of shrimps was reduced by approximately a factor of two when the product was irradiated with a dose of 1 kGy in the chilled state (Vyncke and Declerk, 1972). In the frozen product, a radiation dose of 3 kGy was required to achieve a similar level of microbial reduction (Nouchpramoul, 1982).

Potentially pathogenic *micro-organisms* in shrimps, e.g. *Vibrio parahaemolyticus* and *Shigella*, are substantially reduced with a radiation dose of 1–2.5 kGy (Farkas, 1987; Bandekar *et al.*, 1987). In this dose range, at temperatures below 10°C, normal spoilage of the product should occur before the outgrowth and production of *toxin* of *Clostridium botulinum* (Eklund, 1972). Good manufacturing practice is essential in the handling of the product.

Guidelines

A Code of Good Irradiation Practice for the Control of Microflora in Fish, Frog Legs and Shrimps, ICGFI Document No. 10 (1991) is published by the International Atomic Energy Agency, Vienna.

Product characteristics

The sensory characteristics and storage life of the product will depend on a number of factors, including the initial quality, pre-irradiation conditions, such as blanching time, time elapsed between catch and irradiation, *packaging* and post-irradiation temperature.

Undesirable changes in appearance, odour and *flavour* are associated with chilled shrimps, treated with doses in excess of 2 kGy. There is a risk that changes may occur at doses as low as 1 kGy. In general, a good quality product is obtained using 1–1.5 kGy (Nickerson *et al.*, 1983). In this dose range, the shelf-life of chilled shrimps was increased two- or threefold.

When irradiated in the frozen state, the sensory quality of shrimps was satisfactory at doses of the order of 4–5kGy (Hau *et al.*, 1992; Ito *et al.*, 1989). In this dose range, the shelf-life of shrimps, frozen at −10°C, was doubled. An irradiation odour may be detected at 3 kGy (Hammerton *et al.*, 1992). In order to preserve the quality of the product, irradiated frozen shrimps should be stored at −18°C for no longer than 4 months (Nouchpramoul, 1982).

Detection

Electron spin resonance is the recommended method of detecting irradiated shrimps and prawns.

Potential application

There is legal clearance for irradiation of shrimps in several countries (see Table 10, page 86). In general, a maximum dose of 5 kGy is permitted for the treatment of the frozen product. The process is used commercially in France (see Table 5, page 32). The costs and benefits of the microbial decontamination of frozen shrimps have been evaluated (Borsa and Iverson, 1993).

See also Detection; Fish; Micro-organisms – relative resistance; Micro-organisms – safety; Seafood.

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Sievert

The sievert (Sv) is the SI unit of dose equivalent used in radiation protection. It is defined as the dose of *ionizing radiation* producing the same biological effect in humans as a dose of 1 Gy from *gamma rays* or fast *electrons* (units, joules per kg). It replaces the older term, the *rem* (1 Sv = 100 rem).

Simian virus *see* Viruses.

Solanine *see* Potatoes.

Soya bean *see* Legumes.

Sous vide

Sous vide refers to a means for preserving foods in well-controlled chill storage, based on a process involving mild non-sterilizing heat processing of the food after it has been vacuum packed (Mossel and Struijk, 1991). The foods fall into the class called 'REPFEDS' (refrigerated, processed foods of extended durability) by Notermans *et al.* (1990). Whilst the mild heat processing regimes are generally designed to be sufficient to inactivate non-sporeforming food poisoning *micro-organisms*, there has been a desire to reduce the intensity of the heat treatment, with consequent improvement in product quality. To this end, Shamsuzzaman *et al.* (1992) reported the effective elimination of *Listeria monocytogenes* from inoculated sous vide *chicken* by an *electron beam* dose of 2.9 kGy coupled with heating to an internal temperature of just 65.6°C.

See also Combination treatments.

References

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Soya bean *see* Legume.

Soya sauce

Treatment of Chinese soya sauce with a dose of 5 kGy is reported to eliminate microbial pathogens and improve the sensory quality of the product (Jingtian and Xinhua, 1988).

See also Legislation

Reference

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Spices

Allspice
Anise
Basil
Bay
Caraway
Cardamom
Cayenne
Celery leaves
Celery seeds
Charlock
Chives
Cinnamon
Clove
Coriander
Cumin
Curry
Dill
Fennel
Fenugreek
Garlic powder
Ginger
Juniper
Lemon peel
Mace
Marjoram
Mint
Mustard seed
Nutmeg
Orange peel
Oregano
Paprika
Parsley
Pepper: black, white, red
Sage
Tarragon
Thyme
Turmeric
Vanilla

Mixed seasonings
Condiments (spices that have other flavour enhancers added)

For insect disinfestation and microbial decontamination in all of the spices listed, the recommended dose is 5–10 kGy.

Treatment

Spices, in their natural state, contain a large number of *micro-organisms* capable of causing spoilage of foods to which they are added, e.g. *meat* products. A wide range of bacterial and fungal species have been identified in spices, including organisms of public health significance, such as *Bacillus* spp., *Salmonella*, *Clostridium perfringens*. The *mould* species, *Penicillium*, *Aspergillus flavus* and *A. glaucus* are common, and hence aflatoxins may be present.

The effects of irradiation on spices have been reviewed by Farkas (1988); Narviaz *et al.* (1989); Schuttler and Bogl (1990); Schuttler *et al.* (1991); and IAEA (1992). The radiation dose requirement for spice treatment depends on the number and types of *micro-organisms* present and the chemical composition of the spice. Doses of 3–10 kGy reduce the total aerobic viable cell counts below 10^3 to 10^4 per gram. This treatment is considered to be approximately equivalent to other commercially established processes e.g. fumigation.

Product characteristics

Spices and herbs are dry products and are relatively resistant to *ionizing radiation*; in general, they can tolerate doses up to 10 kGy. The approximate threshold doses causing sensory changes in a range of spices and herbs have been established (Farkas, 1988). Changes in odour and *flavour* may occur, above 15 kGy, depending upon a number of factors, including the individual product, age of seasoning, storage temperature, humidity and *packaging*.

Chemical constituents of herbs and spices are largely unchanged. There may be an increase in extractability of irradiated products, which results in an apparent increase in the volatile oil yield, *lipid* content and hot water solubles in some spices.

Packaging

In the UK, a range of *packaging* materials are approved for use with irradiated spices:

- Hessian sacks
- Woven polypropylene sacks
- Multi-ply paper sacks
- Multi-ply paper sacks with polyethylene lining
- Polyethylene-coated multi-ply paper sacks
- Cardboard cartons with polyethylene liners
- Cardboard kegs

Detection

Chemiluminescence and *thermoluminescence* are the recommended *detection* methods for dried materials, including herbs and spices.

Potential application

Spices used to be treated with ethylene oxide to reduce microbial contamination. Now, ethylene oxide is banned in all EC countries, on account of its toxic properties and its potential as a carcinogen. Predictions that irradiation would widely replace fumigation treatment of herbs and spices have not been fulfilled, owing to fears of adverse *consumer* reaction. Alternative technologies are now being used, many of them based on heat treatment, despite the recognition that *flavour* and aroma components are affected (IAEA, 1992).

In a study of the *economics* of irradiation and ethylene oxide fumigation, the cost of irradiation was greater than fumigation, but the advantages of irradiation were considered to offset the increase in price (Modak, 1993).

Irradiation is a recognized method of reducing the microbial load of spices, with minimal effects on sensory properties. Legal clearance is given in many countries worldwide (Table 10, page 86). Several countries, including USA, Belgium, France and the Netherlands irradiate spices for commercial purposes (see Table 5, page 32) and the commercial volumes are increasing (see Figure 13).

See also Clostridium botulinum; Detection; Herbal teas; Labelling; Micro-organisms – relative resistance; Micro-organisms – safety; Moulds; Vegetables – dried.

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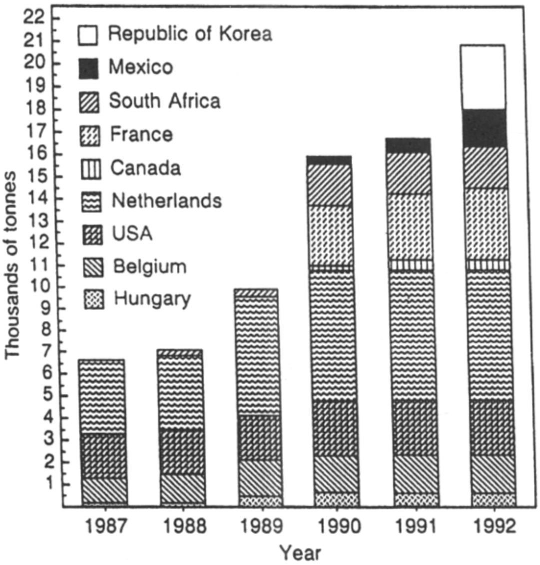

Figure 13 Commercial-scale irradiation of spices and vegetable seasonings (courtesy of the IAEA).

Spores – sensitization to heat

General

Heat and *ionizing radiation* act synergistically in the inactivation of bacterial spores. The effect is most pronounced if the irradiation precedes rather than follows heating, so that irradiation in some way sensitizes the spores to heat (Licciardello and Nickerson, 1962, Gombas and Gomez, 1978). The mechanism of the effect is not known for certain, but Gomez *et al.* (1980) presented evidence to support the hypothesis that radiation-induced breaks in peptidoglycan polymer in the spore cortex, or its decarboxylation, was involved. It is well established that an intact cortex structure is essential for maximal heat resistance.

Grecz *et al.* (1981) investigated the basis of the lethal mechanism at the molecular level and showed that sequential irradiation (0.5–3 kGy) and heating (90°C) of spores of *B. subtilis* and *C. botulinum 62A* were *synergistic* in causing single strand breaks in spore *DNA*.

Practical applications

The fact that irradiation increases the sensitivity of spores to subsequent heating was the basis of the proposal by Kiss and Farkas (1981) to use this *combination treatment* in the thermal processing of spiced *meats*. The heat process required for ensuring commercial sterility in canned luncheon meat could be reduced from F_0 4.7 to F_0 3.4, with consequent gain in quality and saving in energy, if irradiated *spices* were used (Kiss *et al.*, 1978).

Doses of irradiation of 3–4 kGy had little lethal effect on spores of *Clostridium sporogenes* inoculated into luncheon meat, whereas the organism was controlled by a combination of the same radiation dose with a mild subsequent heat treatment (F_0 0.5 to 0.86 minutes), a reduction in pH value (from pH 6.2–6.5 to 5.5–5.7) and a reduction in water activity (a_w from 0.95–10.96 to below 0.95). These reductions were achieved by the addition of lactic and ascorbic acids, and a salt-free enzymatic hydrolysate of soy protein, or the chloride or lactate salts of potassium (Farkas *et al.*, 1992).

Minnaar *et al.* (1992) and Minnaar and McGill (1992) determined the combined heat and irradiation processes that would satisfactorily preserve *mushrooms* in cream and in brine, with respect to the inactivation of spores of *Clostridium sporogenes*, and to the improvement of organoleptic quality.

See also Combination treatment; Micro-organisms – relative resistances; Spices.

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Squash (*Cucurbitaceae*)

Irradiation of summer squash (*Cucurbita pepo*), at doses between 1–3 kGy, controlled decay but promoted softening and deterioration of the appearance of the product (Bramlage and Lipton, 1965).

Reference

Bramlage, W.J. and Lipton, W.J. (1965) *Gamma Radiation of Vegetables to Extend Market Life*, Market Research Report No. 703, Agricultural Research Service, US Department of Agriculture, Washington, DC., p. 9.

Staphylococcus aureus

General

From a public health point of view, *Staphylococcus aureus* is the most important of the more than 20 species of staphylococci. It is a facultatively anaerobic, Gram-positive coccus. Pathogenic strains produce the enzymes coagulase and thermonuclease, and some strains are capable of producing enterotoxins, if they are present and allowed to multiply in foods. It is these *toxins* that cause food poisoning. Generally, numbers of *S. aureus* in excess of 10^6 or 10^7 per gram of food are necessary before sufficient *toxin* is formed to cause disease. The organism is particularly salt-tolerant, and therefore is able to multiply in many cured and otherwise water-activity-reduced foods, if these are contaminated and kept too warm for too long.

The enterotoxins are *proteins*, and seven types are distinguishable antigenically (A, B, C_1, C_2, C_3, D and E). They characteristically cause vomiting and abdominal pain, headaches, muscular cramps and sweating soon (often 6 hours or so) after ingestion, with diarrhoea commonly following on.

Radiation resistance

The *toxins* are very radiation resistant and will survive doses that effectively eradicate the producer organism. *Staphylococcus aureus* cells are relatively sensitive, with *D-values* usually within the range 0.2 to 0.3 kGy or so, according to the components of the suspending medium or food and the conditions during irradiation. Thayer and Boyd (1992) recorded *D-values* just over 0.3 kGy for *S. aureus* in mechanically recovered *chicken* meat irradiated at 0°C.

Reference

Thayer, D.W. and Boyd, G. (1992) Gamma ray processing to destroy *Staphylococcus aureus* in mechanically deboned chicken meat, *Journal of Food Science*, **57**, 848–51.

Starch

Radiation sensitivity

Radiation-induced effects are much greater in isolated starch than when it is a component of foodstuffs. The effects of irradiation on starch are due to the formation of *free radicals*; the intensity of *free radicals* is dependent on starch water content, temperature and duration of storage (Sokhey and Hanna, 1994). Long-lived *free radicals* present after several months of storage in irradiated starches (detected by ESR) are inactivated after the starch has been in contact with water.

Irradiation of starch, below 10 kGy, causes partial depolymerization and fragmentation into simpler molecules (e.g. glucose, maltose, maltotriose, maltopentose) (Diehl, 1983). *Radiolytic products* that are formed include formic acid, acetaldehyde and malonaldehyde.

The product distribution will depend on a number of factors including starch source, presence of other food constituents, water activity and dose.

Microbiological decontamination of starches intended for the food processing industry has been investigated. Over 4 kGy, considerable changes in viscosity, reducing capacity, pH and iodine-binding capacity occur. In the 10 kGy range, dextrin formation and production of monosaccharides have been reported. There is a possibility of using irradiation to obtain modified starches that may have a range of novel applications (Farkas, 1988).

Practical implications

Starch is a major component of *cereal grains*, *legumes* and flours. Changes in irradiated foods, such as softening of *fruits* and *vegetables*, reduction of cooking time in *legumes*, and alteration in the properties of bread dough made from irradiated wheat, are partially due to starch degradation.

The physical and chemical properties of irradiated food starches have been reviewed (Rayas-Duarte and Rupnow, 1989; Sokhey and Hanna, 1994). In general, increasing radiation doses result in an increase in acidity and a decrease in viscosity of starch. In addition, there is an increase in water solubility and a decrease in swelling power of starch granules. Paste property studies indicate that irradiated bean starch produces an easy-to-cook starch with desirable stability during cooking and cooling.

See also Cereal grains; Cereal products; Detection; Fruit and vegetables; Legume; Toxicology.

References

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Sokhey, A.S. and Hanna, M.A. (1994) Properties of irradiated starches, *Food Structure*, **12**(4), 397–410.

Starfruit *see* Carambola.

Sterilization

For long-term storage of food without refrigeration, the recommended dose is 25–70 kGy.

Treatment

Sterilization of *meats*, *fish*, *shellfish* and complete meals by *ionizing radiation* is reviewed by Josephson (1983) and Urbain (1986).

In order to obtain a high quality product, radiation sterilization should only be used on food of high microbiological, sensory and nutritional quality. The following steps are recommended (Josephson, 1983):

1. Inactivate autolytic enzymes: this is achieved by heating products to 70–80°C, prior to packaging.
2. Prevent oxidative and other undesirable physical and chemical changes: sealed packaging materials are used that provide an impermeable barrier to light, moisture, oxygen and micro-organisms. Foods, while still hot, are vacuum packed in sealed metal cans or flexible packages. In addition, food is frozen without delay at an optimum temperature of -40°C.
3. Eliminate organisms that cause spoilage and health hazards: high radiation doses of 25–70 kGy are needed to ensure the absence of *Clostridium botulinum* in the final package.

Product characteristics

Most acceptability ratings of irradiation-sterilized foods have been provided by army personnel for combat rations. Acceptable sensory scores can be achieved for a broad spectrum of shelf-stable *meat, poultry* and *seafood* items (Josephson, 1983; Urbain, 1986). A pre-treatment with sodium tripolyphosphate and sodium chloride has been used to increase the water-holding capacity of irradiated *meat* and *poultry*. An increase in *meat* tenderness, at sterilization doses, appeared to be related to an increase in the water solubility of collagen (Bailey and Rhodes, 1964). Uncured, cooked meats, sterilized in sealed, vacuum-packed containers displayed a pink *colour*, immediately upon opening; in the presence of air, the normal brown/grey *colour* of *meat* quickly developed.

Problems have been encountered in the preparation of certain fishery products. Deterioration, in the form of browning, and loss of *flavour* occurred on storage at ambient temperatures (Urbain, 1986).

Packaging

In order to achieve a high quality radiation-sterilized food, sealed *packaging* that provides an impermeable barrier to *micro-organisms*, light, moisture and *oxygen*, is required. Packages must be sealed under vacuum to prevent rancidity of lipids developing in the foods.

Tinplate rigid containers with epoxy-phenolic enamels and end-sealing compounds made of blends of either cured or uncured butyl elastomers, neoprene and butadiene-styrene elastomers, and neoprene and uncured butyl elastomers have been recommended (Killoran, 1983).

A preformed multi-layer pouch, consisting of nylon film, aluminium foil and intermolecularly bonded polyethyleneterephthlate-polyethylene foil, has been recommended for radiation-sterilized *meat* and *poultry* (Killoran, 1983). Laminated flexible *packaging*, consisting of aluminium foil, and polyester and nylon plies, has been used for irradiated *ready meals* suitable for hikers, sailors and explorers (Anon, 1990).

Nutrition

Research has indicated that no significant impairment of the nutritional value of *protein, carbohydrate* or *lipid* takes place under optimal radiation sterilization conditions (Josephson, 1983). In addition, the process is no more destructive to *thiamine, riboflavin, niacin* and *pyridoxine* than thermal processing.

Shelf-stable foods

The technology of producing shelf-stable foods was developed by the United States Army (at the Quartermaster Food and Container Institute in Chicago 1953–1960) and the US Army Natick (Mass.) Research, Development and Engineering Centre 1962–1980. Toxicological and nutritional studies on *chicken* and *meat* products, sterilized with ionizing energy, were conducted by the US Army until 1980 and then by the USDA in 1984 (CAST, 1989).

Radiation-sterilized food has been used for army rations and for astronauts. Such foods are also available for hikers, sailors and explorers (Anon, 1990). *Ready meals*, including beef stroganoff, lasagne, bobotie, and chicken casserole, are produced in South Africa. Development of a heat-irradiation *combination treatment* to produce shelf-stable *mushrooms* in brine has been described (Minnaar and McGill, 1992).

Sterile hospital diets

Ionizing radiation can be used to treat foods for patients requiring a sterile diet, and is approved for use in the UK, Finland and The Netherlands (see Table 10, page 86).

Foods that have been irradiated for this purpose include *meats, fish, vegetables, dairy products*, breakfast cereals, breads, rolls, crackers, cookies, pastries, condiments, complete meal items, nutritional supplements, snacks, candies, *nuts, gums* and beverage powders (Urbain, 1986). Any cooking that is needed is done prior to irradiation. Foods are frozen at −40°C and irradiated at 25–35 kGy. Most foods are kept at subfreezing until used.

Reducing nitrite in cured meats

Research at the US Army's laboratories at Natick, Mass., in the 1970s, was aimed at using ionizing energy as a substitute for *nitrite* in cured meats (CAST, 1989). Doses of the order of 12–15 kGy provided protection against *Clostridium botulinum*, which was equivalent to or better than that provided by a sodium nitrite concentration of 120 parts per million, in commercially produced bacon. *Nitrite* concentrations of only 20–40 parts per million were needed to maintain the *colour* of the product.

Animal feeds and pet foods

The use of irradiation to destroy *micro-organisms* in pet food, animal feeds and diets of laboratory animals is reviewed by CAST (1989) and Urbain (1986).

Potential application

The majority of approvals worldwide for food irradiation are for doses up to 10 kGy. The use of irradiation to produce radiation-sterilized foods is permitted, in specific countries, for specialized groups of people only, e.g. astronauts, hospital patients requiring a sterile diet (see Table 10, page 86).

See also Animal diets; Clostridium botulinum; Dairy products; History; Legislation; Nitrite reduction; Nutrition; Packaging; Thiamine; Toxicology.

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Urbain, W.M. (1986) *Food Irradiation*, Food Science and Technology Monographs, Academic Press Inc., pp. 133–44 (meat) and 165–9 (fish).

Stone fruits *see* Apricot; Cherry; Nectarine; Peach; Plum.

Strawberry (*Fragaria* spp.)

For shelf-life extension by reducing fungal decay, the recommended dose is 1–2 kGy.

Treatment

Strawberries have a short storage life caused primarily by *mould* growth. The grey mould rot, *Botyris cinerea*, is responsible for decay during refrigerated transit, storage and retail display. In addition, in subtropical climates, 'leak' is caused by *Rhizopus stolonifer*.

The extensive research on the use of irradiation to control fungal disease in strawberries has been reviewed (Thomas, 1986; Barkai-Golan, 1992). Strawberries have been irradiated for commercial use. A radiation dose of the order of 2 kGy increases the shelf-life two- or threefold, in refrigerated storage. Optimal results are obtained with high quality *fruits*, stored in chilled conditions, and irradiated as soon as possible after harvest.

A combination of irradiation and modified atmosphere is reported to give a significant shelf-life extension and preservation of sensory qualities (Marcotte, 1992). Strawberries were pallet wrapped, gassed with 10% carbon dioxide and irradiated with doses of 0.3–1 kGy.

Irradiation of strawberries – a compilation of technical data for its authorization and control, IAEA-TECDOC, is in preparation by the International Atomic Energy Agency.

Product characteristics

At doses less than 2 kGy, changes in the sensory quality of the *fruit* are within acceptable limits. A number of factors affect *flavour* and *texture*, including harvest maturity, cultivar, dose, *packaging*, temperature control and time between harvest and irradiation. Doses in excess of 2 kGy result in softer *texture*, and loss of *colour* and *flavour*.

Reports on the effect of irradiation on levels of *ascorbic acid* in strawberries are not consistent (Thomas, 1986). Losses are minimized by using low radiation doses.

Detection

Detection of *electron spin resonance* signals from achene pips of strawberries is a possible method of detecting irradiated *fruit* (Raffi *et al.*, 1988).

Potential application

Successful marketing trials of irradiated strawberries took place, in France, in 1987 and 1988 (Laizier, 1987; Moog, 1989) (see Table 11, page 98). *Fruit* was irradiated and sold with the label 'Protégé par ionisation' (protected by ionization). The strawberries were sold side-by-side with untreated ones, but at a 30% extra price, and a freshness guarantee of 4 days. Turnover of irradiated strawberries equalled that of the untreated *fruit*.

In 1992, irradiated strawberries were marketed in selected supermarkets in Florida and Chicago (Marcotte, 1992; Pszczola, 1992) (see Table 5, page 32). Irradiated products outsold non-irradiated fruits by 9:1.

See also Electron spin resonance; Fruit and vegetables; Legislation; Market trials.

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Sugar

Irradiation of sugar at a dose of 5 kGy leads to a pinkish discolouration and the formation of various degradation products (Schubert, 1974). Irradiation treatment increased the proportion of reducing sugars.

Reference

Schubert, J. (1974) Irradiation of food and food constituents, in *Improvement of Food Quality by Irradiation*, International Atomic Energy Agency, Vienna, pp. 1–38.

Supercooling

Frozen, irradiated cod, *mushroom* and chicken flesh showed significantly greater supercooling, monitored with a differential scanning calorimeter, than did unirradiated control samples (Nesvabda, 1991). Although there was high variability, it was proposed that the method could have application for the *detection* of irradiated foods. The method has the advantage that it can be applied to water-containing foods, and does not depend on the presence of dry materials, bones or minerals, as does *electron spin resonance* and the luminescence techniques (Kent *et al.*, 1994).

See also Detection.

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Sweetcorn (*Zea mays*); Maize

Control of microbial spoilage of sweetcorn can be achieved using a combination of shrink wrapping and a radiation dose of 0.5 kGy or 1.0 kGy (Deak *et al.*, 1987). The treatment resulted in a three-fold extension of shelf-life. The sensory quality of the product was retained.

Radiation doses in excess of 1 kGy result in 'denting' of sweetcorn kernels (Bramlage and Lipton, 1965).

References

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tion of Vegetables to Extend Market Life, Market Research Report No. 703, Agricultural Research Service, US Dept. of Agriculture, Washington, DC, p. 12.

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Sweet potato (*Ipomoea batatas*)

The sweet potato is a tuber that is grown both in tropical regions and temperate climates; its nutritional value is mainly as a source of *starch*. There is interest in the use of irradiation to inhibit sprouting of sweet potato, and to control *insect* and microbial disease.

The optimum radiation dose required to inhibit sprouting appears to be of the order of 0.1 kGy (Matsuyama and Umeda, 1983). The treatment may increase susceptibility to storage rots. Treatment of sweet potatoes with low doses of irradiation to control *insect* pests, such as weevils, may be feasible. However, doses above 0.5 kGy, appropriate for the control of spoilage by *micro-organisms*, affect the sensory quality and nutritional value of sweet potato storage roots (Lu *et al.*, 1986). Biochemical changes that take place in irradiated sweet potatoes are reported by Ajlouni and Hamdy (1988).

See also Inhibition of sprouting; Insects.

References

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Sweet potato wine *see* Wine.

Synergism

In food technology, synergism is the combined effect of preservation technologies that exceeds the sum of their individual effects, e.g. *combination treatments* using irradiation and heat.

T

Taenia *see* Parasites.

Tangerine *see* Orange.

Tapeworm *see* Parasites.

Temperature

Radiation-derived *free radicals* are much more mobile, and therefore freer to react, in liquid than in solid systems. Therefore, it is generally found that freezing raises the resistance of the *micro-organisms* in foods by minimizing the indirect effects of radiation. At the same time, freezing may, for the same reasons, reduce the extent of radiation-induced damage to the many small molecules that contribute to food *flavour*. These molecules are generally influenced more by the indirect than the direct action of radiation, and freezing acts mostly to suppress indirect effects.

Although microbial resistance increases on freezing, this is generally far outweighed by the organoleptic benefits of irradiating in the frozen state. The extent of microbial protection that can occur is illustrated in Figure 14 (Goldblith, 1971).

See also Direct and indirect action of ionizing radiation; Micro-organisms – relative resistances.

Reference

Goldblith, S.A. (1971) The inhibition and destruction of the microbiological cell by radiation, in *Inhibition and Destruction of the Microbial Cell*, (ed. W.B. Hugo) pp. 285–305, London, Academic Press.

Temperature rise

There is a temperature rise associated with the irradiation of food. However, this rise is small. For a food with a heat capacity approximately the same as water, an absorbed dose of 10 kGy would cause a temperature rise of about 2.4°C.

Texture

Softening is the primary factor limiting the practical application of irradiation to *fruits* and *vegetables*. Changes in texture are caused by radiation-induced depolymerization of *pectin*, *cellulose* and *starch* (Urbain, 1986). The same mechanism is responsible for the decrease in the cooking time of irradiated *dried vegetables* and *legumes*. Irradiation induces a loss of viscosity in certain gelling and thickening agents.

See also Gelling agent; Fruit and vegetables.

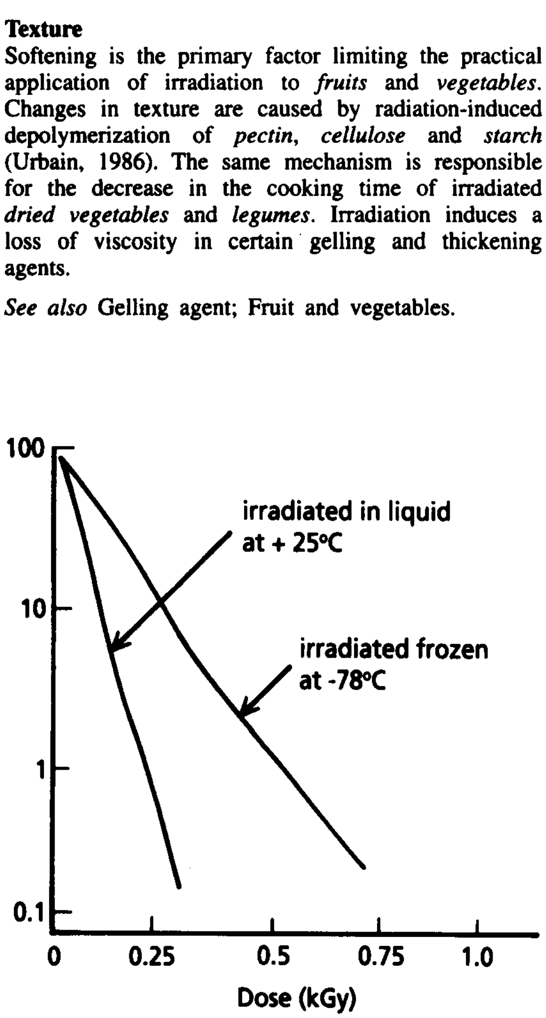

Figure 14 Effect of freezing on resistance of *Escherichia coli* irradiated in broth (from Goldblith, 1971).

Reference

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Thermoluminescence

When certain types of foods are irradiated, a small fraction of the absorbed energy remains stored in activated atoms and molecules. When the temperature of the food is raised sufficiently, this absorbed energy is released as photons of light ('thermoluminescence'), which can be detected, for instance, with a sensitive photomultiplier instrument (Sanderson *et al.*, 1994). The amount of light emitted can then be correlated with the irradiation dose originally absorbed. The technique is particularly applicable to relatively dry foods, in which the signal remains stable during long periods of storage, e.g. more than a year for some *spices*.

Thermoluminescence can also be used for foods which have been irradiated and stored frozen. In these foods, water has essentially been removed as ice, which is analogous to removal of water by drying. In wet foods, the technique is of less value, because any initial signal induced by irradiation normally decays rapidly.

Although the magnitude of the thermoluminescence signal depends greatly on product type as well as on absorbed dose, numerous trials have confirmed the efficacy of the test for low water content food ingredients, such as *dried vegetables*, herbs and *spices* (Heide and Bogl, 1988; Kolbak, 1988; Moriarty *et al.*, 1988). In addition, thermoluminescence can be used to detect low doses of irradiation used to inhibit sprouting (Schreiber *et al.*, 1994).

See also Chemiluminescence; Detection; Inhibition of sprouting; Photostimulated luminescence.

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Thiamine (vitamin B1)

General

The major nutritional sources of thiamine are *nuts*, *pulses*, and whole *cereal grain* products. Levels are high in bran-containing flours and bread, but not in white flours or bread, unless thiamine has been deliberately added to them. Small amounts are derived from *meats*, particularly pork.

The thiamine molecule may undergo oxidation or reduction and is particularly sensitive to rupture of the C-N bond of the methylene-linked pyrimidine nucleus and thiazole ring.

A substantial lack of thiamine leads to the disease beriberi. Less extreme effects of thiamine deficiency include interference with the transmission of nerve impulses, weakness and general tiredness.

Radiation sensitivity

Irradiation of thiamine causes deamination and destruction of the pyrimidine ring (Groninger and Tappel, 1957) with loss of biological activity (Ziporin *et al.*, 1957). Thiamine is relatively radiation sensitive in some foods.

Low disinfestation doses of 0.25–0.35 kGy, delivered to *cereal grains* resulted in losses of thiamine of 20–40% (Diehl, 1975). In cooked *pork* chops, irradiated at 0.3 and 1.0 kGy (the dose range proposed for trichina control), losses were 5.6 and 17.6% (Fox *et al.*, 1989). It is calculated that loss of thiamine in the American diet, due to irradiation of *pork* chops and roasts, would be 1.5% at 1 kGy.

When radiation doses as high as 25 kGy were used, raw *fish* retained nearly 40% of total thiamine (Brooke *et al.*, 1966), and treatment of clams, at 45 kGy, led to no detectable loss of thiamine (Brook *et al.*, 1964). Following a major US study of the potential nutritional and toxicological effects of radiation *sterilization* on chicken breasts, Black *et al.* (1963) concluded that γ-irradiation, at doses between 45–68 kGy, reduced thiamine levels to a similar level as that produced by heat sterilization.

See also Vitamins.

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Thickening agents *see* Agar; Alginate; Carrageenan; Gums; Pectin and cellulose; Starch.

Tocopherols (vitamin E)

General

The major dietary sources of the E-vitamins are seeds, *nuts*, vegetable oils, *vegetables* and *fruits*. The E-vitamins are not synthesized by animals.

Chemically there are at least eight distinct and biologically active vitamin E molecules which differ one from the other in the positions and numbers of methyl groups in the aromatic ring of their common G-chromanol ring structure. They include the α-, β-, γ- and δ-tocopherols and the α-, β-, γ- and δ-tocotrienols.

The various E-vitamins are resistant to heat but, being strong antioxidants, they oxidize slowly and lose activity in air. It is thought that their major functions *in vivo* are as antioxidants, protecting membrane lipids from *free radical*-initiated damage. However, it is also suspected that they most probably have other yet to be elucidated functions too. Deficiency leads to weakening of muscles and has been associated with reproductive disorders and premature birth.

Radiation sensitivity

Vitamin E is the most radiation-sensitive of the fat-soluble vitamins. A dose of 400 kGy reduced levels in iso-octane by more than 95% (Knapp and Tappel, 1961), and in tributyrin by even more. At more practical doses, a sterilizing dose for *beef* (30 kGy) reduced α-tocopherol levels by about 60% in air, but not significantly in nitrogen. Alpha- and gamma- tocopherols decreased similarly in irradiated chicken breast (Lakritz and Thayer, 1992). Oats irradiated at a dose of 1 kGy had lost only 5% tocopherol after 8-months storage in nitrogen, but nearly 60% when stored in air (Diehl, 1979). Diehl (1980) reported a near 20% loss following 1 kGy irradiation of hazel *nuts*.

See also Vitamins.

References

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Tomato (*Lycopersicon esculentum*)

Irradiation could be used for insect disinfestation and for shelf-life extension, either by delaying ripening and senescence or by reducing microbial spoilage.

Insect disinfestation

The use of irradiation to control *insect* infestation by the Queensland fruit fly has been investigated (Jessup *et al.*, 1992). A dose of 0.1 kGy, which would prevent the development of the adult insects, did not affect the quality of the *fruit*.

Shelf-life extension

There is contradictory evidence on the effectiveness of irradiation to increase the shelf-life of tomatoes (Thomas, 1988). A number of factors affect results, including the developmental stage or maturity of the *fruit* at the time of irradiation, varietal variations, radiation dose, and storage temperatures.

Doses of 0.1 kGy, and above, result in a delay in *ripening* of tomatoes. Green mature *fruits* may fail to develop a uniform red *colour*. *Fruits* irradiated in the 'pink' stage can tolerate higher doses and these fruits appear to develop a normal red *colour*.

The development of fungal decay in tomatoes, caused mainly by *Alternaria*, *Botrytis* or *Rhizopus* spp., can be controlled using doses of order of 3 kGy. At this level, softening and the loss of characteristic *flavour* of the *fruits* occur. A combined treatment of mild heat (45°C for 5 minutes) and low-dose irradiation (1.2 kGy) has been suggested as an effective treatment for preventing *mould* rot without adverse effects on quality in tomatoes (Stegeman, 1982).

Potential application

In China, legal clearance is given for irradiation of tomatoes to increase their shelf-life (see Table 10, page 86). Irradiated tomatoes have been on sale in the USA (Corrigan, 1993).

References

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Toxicology

General

Studies of the chemical changes that occur in foods when they are irradiated have shown that low levels of *radiolytic products* are formed. Many of these are identical to the chemicals that are formed in foods treated by other means, e.g. by heat. It was these observations, along with the extensive toxicological studies carried out in the mid-1900s, that led to the view that health hazards from the compounds detected were probably negligible (WHO, 1977). However, further studies, particularly with respect to so-called '*unique radiolytic products*' (URPs) were recommended.

Consideration of toxicological studies, which were made using a wide variety of foods, by a Joint FAO/WHO/IAEA Expert Committee (WHO, 1981), led to the conclusion that irradiation of any food commodity up to an overall average dose of 10 kGy presents no toxicological hazard. It was therefore recommended that toxicological testing of foods so treated should no longer be required.

Radiolytic products

The *radiolytic products* that arise in irradiated foods mostly derive from highly reactive, short-lived *free radicals* generated from water. These are predominantly *hydrogen radicals* (H•), *hydroxyl radicals* (OH•) and *hydrated electrons* (e–aq), which rapidly undergo further reactions to generate a wide variety of other short-lived species and, eventually, more stable products.

An exception to the rapid disappearance of the first-formed radicals is in solid, dry and frozen foods. *Free radicals* may be sufficiently long-lived to form the basis for *detection* methods for irradiated foods.

The general primary reactions of water undergoing ionizing irradiation include:

$$
\begin{aligned}
&\mathrm{H_2O} \longrightarrow \mathrm{H_2O^+} + e^- \\
&e^- + \mathrm{H_2O} \longrightarrow \mathrm{H_2O^-} \\
&\mathrm{H_2O^+} \longrightarrow \mathrm{H^+} + \mathrm{OH^\circ} \\
&\mathrm{H_2O^-} \longrightarrow \mathrm{H\bullet} + \mathrm{OH^-}
\end{aligned}
$$

Further reactions may then occur to generate a wider variety of water derived products (Hughes, 1983), e.g.:

$$
\begin{aligned}
&\mathrm{H\bullet} + \mathrm{H\bullet} \longrightarrow \mathrm{H_2} \\
&\mathrm{OH\bullet} + \mathrm{OH\bullet} \longrightarrow \mathrm{H_2O_2} \\
&\mathrm{H\bullet} + \mathrm{OH\bullet} \longrightarrow \mathrm{H_2O} \\
&\mathrm{H\bullet} + \mathrm{H_2O} \longrightarrow \mathrm{H_2} + \mathrm{OH\bullet} \\
&\mathrm{OH\bullet} + \mathrm{H_2O_2} \longrightarrow \mathrm{H_2O} + \mathrm{HO_2\bullet} \\
&\mathrm{H\bullet} + \mathrm{O_2} \longrightarrow \mathrm{HO_2\bullet}
\end{aligned}
$$

Whilst always formed during the irradiation of wet foods, these chemical species are not unique to irradiation. Most of them are generated by a wide range of naturally occurring oxidative enzymes or reactions of organic materials catalysed by visible light ('photoactivation': Robinson, 1986).

See also Detection; Ionization.

References

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Toxins

The toxins that may be produced in foods during the growth of toxigenic bacteria such as *Staphylococcus aureus* and *Clostridium botulinum* are proteins and are far more radiation tolerant than the *micro-organisms* that produce them. This is particularly so when the toxins are present in real foods, as opposed to water, or dilute solutions of buffer salts. This is because of the substantial quenching of radiation-derived *free radicals* that occurs in foods and results in protection of individual protein molecules.

The *toxin* of *C. botulinum* type E was found by Skulberg (1965) to have a *D-value*, when irradiated in a rich bacteriological medium, of about 21 kGy, which is more than ten times greater than that of spores of the producer-organism. The *D-value* for type A *toxin* was nearer to 40 kGy.

Neither irradiation nor heat processing can be relied on to eliminate staphylococcal toxins that might be formed during poor temperature control of stored foods (Modi *et al.*, 1990).

Irradiation of foods at the commonly recommended doses must not, therefore, be expected to reduce the levels of any such toxins that may have been preformed in a food, e.g. by incorrect storage prior to irradiation.

See also Micro-organisms – relative resistances.

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Toxoplasma *see* Parasites.

Trace elements *see* Minerals and trace elements.

Tragacanth gum *see* Gums.

Trichina *see* Parasites.

Tropical and subtropical fruits

The effects of irradiation on a number of tropical *fruits* including the ber (*Zizyphus jujuba*), soursop (*Anona muricata*), the loquat (*Eriobotrya japonica)* and passion fruit (*Passiflora edulis*) are reviewed by Thomas (1988). A delay in *ripening* in response to low doses of *ionizing radiation*, which is observed with certain tropical fruits, could have *economic* implications.

See also Banana; Carambola; Guava; Longan; Mango; Mangosteen; Papaya; Persimmon; Pineapple; Rambutan; Sapota.

Reference

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Tubers *see* Artichoke – Jerusalem; Potato; Sweet potato; Yam.

Turkey

The majority of studies on the irradiation of *poultry* meat have used chicken. There may an increased risk of *off-flavour* development in turkey meat (Sudarmadji and Urbain, 1972).

In oxygen-impermeable *packaging* film, irradiation of chilled turkey breast fillets, at 2.5 kGy, resulted in an intense pink *colour* in the raw and cooked samples, together with an unpleasant raw odour (Lynch *et al.*, 1991). The odour did not dissipate on storage. In oxygen-permeable film, sensory properties of the irradiated turkey were acceptable after 21 days; the pink appearance was liked by the sensory panel.

In turkey frankfurters, made with 2.5% sodium chloride, a radiation dose of 5 kGy induced *off-flavour* development (Barbut *et al.*, 1988). In frankfurters containing 1.5% NaCl, plus sodium tripolyphosphate, little difference in *flavour* was found between the treated and non-treated product. Phosphates may play an antioxidant role in the irradiated turkey frankfurters.

See also Poultry.

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Turnip

In turnips, radiation doses in the range of 0.05–0.15 kGy have been reported to inhibit sprouting (Mikaelsen, 1959), although the rate of rotting may be higher after treatment.

Reference

Mikaelsen, K. (1959) Irradiation of root crops, *International Journal of Applied Radiation and Isotopes*, **6**, 171–3.

o-Tyrosine (ortho-Tyrosine)

Irradiation of the amino acid phenylalanine results in the formation of o-tyrosine. This compound has therefore been proposed as a suitable marker for *detection* of the irradiation of high-*protein* foods, such as *meat*, *poultry* and *fish* and derived products (Karam *et al.*, 1984; Karam and Simic, 1988). o-Tyrosine can be detected by conventional high-performance liquid chromatography after suitable derivitization.

An HPLC-fluorescence method that allows quantification of 0.1 ng of o-tyrosine was developed by Chuaqui-Offermans and McDougall (1991), who found a linear relationship with irradiation dose in chicken meat. Strict derivation of dose from measured levels of o-tyrosine may be hampered by the influence of temperature and dose rate on yield, and on the fact that o-tyrosine has been detected in some (non-irradiated) tissues. However, the simplicity of the methodology for a relevantly equipped analytical laboratory, suggests that the technique will be valuable, along with others, for protein-rich foods.

Szekely *et al.* (1992) studied the toxicity of o-tyrosine to cultured cells and found that levels far in excess of those produced in irradiated foods were needed to cause any genotoxic effects.

See also Detection; Toxicology.

References

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U

Unique radiolytic products (URPs)

The reaction of the *free radicals* generated by irradiation with *food components* gives rise to a very wide range of *radiolytic products*, because the action of radiation is quite non-selective. By far the majority of these products are identical to products that are found naturally in foods or are generated in foods during the application of other processes, such as pasteurization, canning, roasting, grilling, toasting, etc. Examples include glucose, formic acid, acetaldehyde and carbon dioxide. The safety of these *radiolytic products* has been examined critically and no evidence of harmfulness found.

However, so-called unique radiolytic products (URPs) have been reported occasionally, i.e. products of food irradiation that have *not* been detected in other foods or processes (Merritt, 1972). Whilst there is no indication from the numerous toxicological studies that have been undertaken that URPs constitute a hazard, they are still sought (WHO, 1994). One reason for interest in URPs is that, if truly unique, they could form the basis of *detection* tests for irradiated foods.

See also Detection; Radiolytic product; Toxicology.

References

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WHO (1994) *Safety and Nutritional Adequacy of Irradiated Food*, World Health Organization, Geneva.

V

Vegetables *see* Fruit and vegetables; Vegetables – dried; Vegetables – cut, prepacked.

Vegetables – dried

To reduce microbial contamination, the recommended dose is less than 5 kGy.

Treatment

Dried vegetables, which are commonly used as soup ingredients, contain a large number of *micro-organisms* capable of causing spoilage. A radiation dose of 5–10 kGy reduces contamination depending on the organisms present. *Yeasts* and bacterial spores are more radiation resistant than Enterobacteriaceae. A number of dehydrated vegetable products have been investigated, including *asparagus*, *peas*, *carrot*, *celery*, *mushroom*, *tomato*, yellow boletus, french beans and parsley root (Kiss *et al.*, 1974; Diehl, 1983; Farkas, 1988).

Insect pests, which are controlled by doses of 1 kGy and below, would be destroyed by radiation treatment appropriate for microbial decontamination. Losses, caused by weevils, of dry green beans used for bean sprouts, could be reduced by irradiation with no change in germination or rootlet length (Lan *et al.*, 1991).

Product characteristics

Dehydrated products are less sensitive to radiation damage than those containing water. Dried vegetables can tolerate higher radiation doses than fresh vegetables. Changes in *flavour* and *colour* are minimal in some products, even at doses of 10 kGy (Kiss *et al.*, 1974). However, certain vegetable products, e.g. *asparagus*, *mushrooms* and *onions*, undergo browning.

Irradiation, above 5 kGy, decreases the cooking time requirement for dried vegetables (Farkas, 1988; Kiss *et al.*, 1974; Diehl, 1983). Irradiation causes partial breakdown of *cellulose*, *pectin* and *starch*, and mobilization of calcium in the plant tissue. This results in a decrease in product hardness and an increase in absorption capacity of the dried product. In a dry soup mixture, containing a number of vegetable ingredients, there may be a need to adjust the dose for each product, in order to secure a uniform tenderness in the cooking and rehydration period (Farkas, 1988).

Potential use

Irradiation of dehydrated vegetables is given legal clearance in a number of countries (see Table 10, page 86) and is used commercially (see Table 5, page 32).

See also Dried foods; Micro-organisms – relative resistances; Legislation; Spices; Water activity.

References

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Vegetables – cut, prepacked

Storage of cut vegetables is limited by initial microbial contamination, coupled with rapid growth during storage; other problems affecting quality include discolouration, loss of weight and desiccation. *Packaging* and cooling may ameliorate these factors but do not offer complete control. There is interest in the possibility of using irradiation to increase the shelf-life of cut, prepacked vegetables.

In cut, washed and packaged leeks, cauliflowers, *carrots* and *onions* (Langerak and Damen, 1978), the reduction in total viable count depended on radiation dose and *micro-organisms* present. A shelf-life of more than 4 days was achieved, with a dose of 1 kGy, compared with 1 day for the untreated samples. Changes in *flavour* and *colour* were minimal at doses of 1 kGy; *colour* deterioration appeared to restrict shelf-life in the irradiated samples. At doses in excess of 1 kGy, softening of prepared sliced carrots is reported (Beczner-Hegyesi *et al.*, 1972). Optimal hygienic and sensory properties of grated *carrot* were achieved with a treatment of 0.5 kGy and storage at 4°C (Biosseau *et al.*, 1991).

See also Fruits and vegetables.

References

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Vibrio

General

The genus *Vibrio* includes small comma-shaped *micro-organisms*, several species of which are pathogenic for humans. The type species is *V. cholerae*, which causes the disease cholera. The most important types of *V. cholerae* are those in serogroup O:1, which is subdivided into two biotypes: *cholerae* and *El Tor*. The organism colonizes the intestinal tract, as does enterotoxigenic *Escherichia coli*, producing a *toxin* that causes massive accumulation of fluid in the gut and dehydration of the host. Cholera is predominantly water-borne, in environments lacking effective sanitation and hygiene, but is also transmitted by some types of contaminated foods that pick up the organism from infected waters, such as crabs, raw oysters and other *shellfish* (Madden *et al.*, 1989).

Vibrio parahaemolyticus is an obligate halophile, requiring sodium chloride for growth, and therefore most often associated with the marine environment and *seafoods*. It is therefore, not unsurprisingly, the main cause of food-borne disease in Japan, where large quantities of raw *fish* are consumed (Twedt, 1989).

Vibrio vulnificus is also halophilic, and therefore has been associated with food-poisoning outbreaks traced to contaminated *seafoods*, such as oysters and clams. Although less common than *V. parahaemolyticus*, it is more virulent, sometimes causing septicaemia and death in over 40% of cases (Oliver, 1989).

Other food-associated vibrios have been connected with food poisoning, but with far less significance than *V. cholerae*, *V. parahaemolyticus* and *V. vulnificus* (Blake *et al.*, 1980).

Radiation resistance

Radiation resistance of all the *Vibrio* species is low. For example, a number of strains of *V. parahaemolyticus* in crab meat were inactivated to the extent of 10^2- to 10^5-fold by a dose of 2.5 kGy (Matches and Liston, 1971).

See also Seafood.

References

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Twedt, R.M. (1989) Vibrio parahaemolyticus, in *Foodborne Bacterial Pathogens*, (ed. M.P. Doyle) pp. 543–68, Marcel Dekker, New York.

Viruses

General

Virus particles generally have small complements of *DNA* or RNA and therefore represent small targets for the direct effects of *ionizing radiation*, compared with the larger nucleic acid targets in *bacteria*, and still larger targets in most eukaryotic cells.

Radiation resistance

The radiation tolerance of viruses is high. For example, the *D-value* for inactivation of Vaccinia virus, dried and *in vacuo* was 1.7 kGy, whilst that of Foot-and-Mouth virus, irradiated at −60°C, was as high as 12 kGy (Goldblith, 1971).

Sullivan *et al.* (1971) compared the *gamma radiation* resistances of 30 viruses, including strains of Adenovirus, Cocksackie virus, Echovirus, Poliovirus, Herpes

Simplex virus, Newcastle disease virus, Reovirus, Simian Virus and Influenza virus. When suspended in water, their *D-values* ranged from 1.0 to 1.4 kGy but, when suspended in a more complex medium (Eagle's minimum essential medium), resistance increased markedly, and *D-values* ranged from 3.0 to 5.3 kGy.

The large effect of the menstruum on the irradiation resistance of viruses has been observed, not only in laboratory media containing added organic matter, such as serum (Grecz *et al.*, 1983), but also in broth media in which the soluble nutrients levels have been raised, and in foods. For example, the resistance of the bacterial virus, bacteriophage T7, irradiated in nutrient broth, rose from D = 0.3 kGy to D = 2.8 kGy as the solids concentration in the broth was raised from 0.4 to 12.8% (Dewey, 1972). The radiation *D-value* of Cocksackie virus B2 rose from 1.4 kGy in water at 0.5°C to 7.6 kGy when irradiated in cooked ground *beef* at the same temperature (Sullivan *et al.*, 1973). When irradiated at -90°C, the resistance of the virus in water was greatly increased to a *D-value* of 5.3 kGy though less dramatically raised in *beef* to 8.1 kGy.

See also Micro-organisms – relative resistances.

References

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Viscometry

Alwis and Grandison (1992) measured the viscosity of black pepper samples that had been irradiated then alkalinized, after heat gelation, in water. The samples showed a loss of viscosity at doses (4.6 and 9.6 kGy) relevant to *spice* decontamination. They proposed that the method could be used to detect pepper irradiation.

See also Detection.

Reference

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Vitamin A *see* Retinol.

Vitamin B1 *see* Thiamine.

Vitamin B2 *see* Riboflavin.

Vitamin B5 *see* Niacin.

Vitamin B6 *see* Pyridoxine.

Vitamin B10 *see* Biotin.

Vitamin B12 *see* Cyanocobalamin.

Vitamin C *see* Ascorbic acid.

Vitamin D *see* Calciferol.

Vitamin E *see* Tocopherols.

Vitamins

Some vitamins are well known to be sensitive to the effects of *ionizing radiation*. Their inactivation (i.e. loss of biological activity) results predominantly from reactions with *free radicals* and other reactive species generated by the radiolysis of water in foods. Since these reactive molecules will interact with a wide variety of *food components*, the exact effect of irradiation on a particular vitamin will depend not only on the chemical nature of the particular vitamin, but also vary greatly with the nature of the food itself. *In vitro* studies, in which dilute solutions of vitamins have been irradiated, may indicate sensitivities that are never seen in foods, where substantial 'quenching' by competitor molecules usually occurs (Goldblith, 1955).

Reactivity of individual vitamins varies according to their chemical nature (WHO, 1994). The most important with respect to food irradiation, include the **water soluble vitamins**: *ascorbic acid* (vitamin C); *thiamine* (vitamin B1); *riboflavin* (vitamin B2); *niacin* (vitamin B5); *biotin* (vitamin B10); *folic acid* (pteroylglutamic acid); *pyridoxine* (vitamin B6); *pantothenic acid*; *cyanocobalamin* (vitamin B12); and the **fat soluble vitamins**: *retinol* and some of its derivatives (vitamin A); *calciferol* and some of its derivatives (vitamin D); *tocopherols* (vitamin E); naphthaquinone derivatives (vitamin K).

See also Nutrition.

References

Goldblith, S.A. (1955) Preservation of foods by ionizing radiations, *Journal of the American Dietetic Association*, **31**, 243–9.

WHO (1994) *Safety and nutritional adequacy of irradiated food*, World Health Organization, Geneva.

Volatiles

Irradiation of foods, particularly those containing high levels of lipids, generates volatile products of *lipid* breakdown. These may be present at concentrations sufficient for *detection* by sensitive gas chromatographic (GC) analysis.

The nature of the volatiles depends on the composition of the fat in the irradiated food, whilst their quantity depends on the radiation dose. For example, the high oleate, palmitate and stearate levels in *pork* lipids act as precursors of the hydrocarbons 8-heptadecene, 1,8-hexadecadiene, pentadecane, 1-tetradecene, heptadecane and 1-heptadecene. These are detected following *lipid* extraction and fractionation, vacuum distillation and GC analysis (Nawar, 1988). Once formed, the hydrocarbons are stable. Their analysis is not interfered with by other *food components* or processes. Although equipment costs are high, the technique will find a niche as a method of *detection* in food irradiation technology.

Morehouse *et al.* (1993) reported that capillary GC detected radiolytically-generated hydrocarbons that increased linearly with absorbed dose in irradiated *poultry*, *beef* and *pork*. Two-step HPLC, coupled on-line to a gas chromatograph, improved sensitivity and reduced the level of interfering peaks on chromatograms (Schulzki *et al.*, 1994).

Very low levels of many other volatile products may be formed. For example, over 100 minor volatiles were identified following high dose (56 kGy) irradiation of frozen *beef*. Their total yield was about 9 mg per kilogram of *beef*. Most of them are known to occur at various levels in unirradiated foods (see Federation of American Societies for Experimental Biology, 1977 and Supplements 1 and 2, 1979).

See also Detection.

References

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W

Walnut *see* Nut.

Water *see* Ionization.

Water activity
It is generally found that *micro-organisms* are more radiation-resistant in *dried foods* than in wet foods. This is analogous to the increase in resistance that accompanies freezing, during which water is essentially removed from foods, as crystals of ice, so that the environment in the food becomes drier, and the water activity is consequently reduced. Again, by analogy to freezing, the lack of solvent water reduces mobility of the small molecular weight products of radiolysis so that mostly the indirect effects of radiation are suppressed.

Certainly, at very low water activities, the radiation resistance of most *micro-organisms* in *dried foods* is enhanced. With less extensive drying, the effect is often not great, and cells in foods dried to intermediate levels of water activity/water content may actually become more sensitive to radiation than in 'wet' foods.

These extremes are well illustrated in the sensitivity pattern of *Staphylococcus aureus* shown in Figure 15 (Goldblith, 1971).

See also Direct and indirect action of ionizing radiation; Dried foods; Temperature.

References

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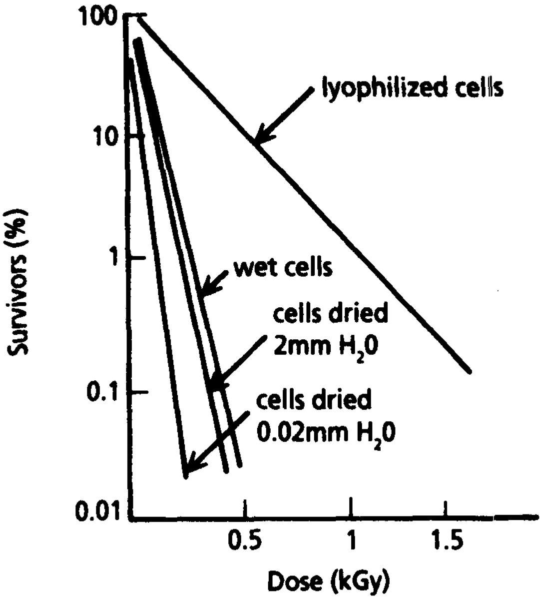

Figure 15 Effect of drying on resistance of *Staphylococcus aureus*. The figure shows the small increases in sensitivity that can accompany partial drying as well as the substantial increase in resistance that can result from extreme drying by lyophilization (from Goldblith, 1971).

Wheat *see* Cereal grains; Cereal products; Immune response; Polyploidy.

WHO (World Health Organization) *see* FAO/IAEA/WHO.

Wholesomeness
The various studies of the *safety* and acceptability of irradiated foods address their 'wholesomeness' (e.g. WHO, 1981; Report, 1986). The term is used to cover *all* those aspects of food irradiation that impinge on its acceptability, e.g. including microbiological aspects (benefits and potential hazards); toxicological aspects (*radiolytic products*; toxicity and mutagenicity); nutritional aspects (effects on major and trace nutrient *food components*); *induced radioactivity*, etc.

See also Micro-organisms – safety; Nutrition; Toxicology.

References

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Wine

Wine has been irradiated for a number of purposes, including sterilization in order to terminate fermentation and improve stability; changing the normal characteristics of wine; and accelerating ageing (Urbain, 1986).

A radiation dose of 15 kGy is required to inactivate *yeasts* in *grape* must (Galli *et al.*, 1988). This treatment resulted in degradation of *colour* and *flavour* components (phenolic compounds) of irradiated *grapes*. The radiation-induced differences were attenuated by fermentation into wine. Changes in composition and organoleptic properties in the wine were considered to be no more significant than those occurring with other treatments, e.g. heat. The most pronounced effect due to irradiation seemed to be a premature ageing of wines. This is also the case for brandies (Urbain, 1986). At a lower dose, 0.5–2 kGy, the quality of wine fermented from *grapes* was not impaired (Kiss *et al.*, 1974).

Changes in port and wines irradiated in the 1–10 kGy range resulted in a decrease in *colour* and an increase in volatile aldehydes (Singleton, 1963). At the lower end of the dose range, improvement in wine quality was apparent. Radiation doses in the range 6–7 kGy, needed to inactivate fermentation, resulted in undesirable sensory changes.

The quality of *sweet potato* wine was improved by irradiation (Zhou et al., 1990); legal clearance is given in China up to a dose of 4 kGy (see Table 10, page 86) Market testing of the product has been reported in China (Anon, 1990) (see Table 11, page 98).

See also Yeasts.

References

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X

Xanthan gum *see* Gums.

X-rays

X-rays are a form of electromagnetic radiation, with a wide range of short wavelengths. Their characteristics are the same as those of *gamma rays*, except for their origin.

The most important method of producing X-rays depends on a process known as Bremsstrahlung. This term is a German word meaning braking radiation. X-rays are produced when charged particles, moving with a very high velocity, are slowed down rapidly by striking a target. In practice, X-rays are machine generated by directing high-velocity electrons on to a heavy metal target, typically tungsten.

For food treatment, X-ray machines must be operated at an energy level of 5 MeV, or lower. This restriction is based on the need to prevent *induced radioactivity*. X-ray production is relatively inefficient but it can be competitive with *gamma radiation* for high-capacity plants (Farkas, 1988). The possibility of using electrons and X-rays in the same irradiation facility is attractive.

See also Electromagnetic spectrum; Induced radioactivity; Ionizing radiation; Facilities.

Reference

Farkas, J. (1988) *Irradiation of dry food ingredients*, CRC Press Inc., Boca Raton, Florida, p. 84.

Y

Yam (*Dioscorea* spp.)

The yam is a tuber that is a staple *carbohydrate* food crop in west Africa; it is an important crop in south east Asia and regions of the Pacific and the Caribbean.

The causes of *post-harvest losses* in yams are reviewed by Thomas (1983). Sprouting is an important cause of deterioration during storage. The effectiveness of chemical sprout inhibitors appears to vary with the species of yam.

A radiation dose of 0.05–0.15 kGy is recommended for *inhibition of sprouting* during dormancy, but after completion of wound-healing. In comparison with the untreated product, irradiated yams were more palatable and had a better external appearance (Thomas, 1983). Sprouting was inhibited for an 8-month storage period, under ambient tropical temperatures, without causing adverse changes in acceptability or physiological properties. A 50% reduction in weight loss can be obtained. In this dose range, control of the nematode *Scutellonema bradys* is provided.

The *economic* feasibility of irradiation of yams in Ghana has been evaluated (Nketsia-Tabiri *et al.*, 1993).

References

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Yeasts

Radiation resistance

Since yeasts have large cells and contain large quantities of nuclear material when compared with *bacteria* and *viruses*, they represent larger 'targets' for irradiation damage. Consequently, some of them have relatively low resistances to *ionizing radiation*. For example, many yeasts have *D-values* within the range of 0.1 to 0.5 kGy, so that a dose of 5 kGy would be expected to reduce numbers by at least 10 logs. However, some are much more tolerant than this. For example, a particularly radiation-resistant strain of *Saccharomyces cerevisiae* var. *ellipsoideus*, studied by Stehlik and Kaindl (1966), had a *D-value* as high as 3 kGy when irradiated at ambient temperature (about 20°C). As with bacterial spores and some vegetative *bacteria*, the inactivation rate increased greatly as the temperature was raised, so that at 45°C the *D-value* fell to about 0.5 kGy.

Practical implications

In low-dose-irradiated foods, the general radiation resistance of non-spore forming *micro-organisms* increases from that of most Gram-negative species, e.g. *Pseudomonas*, *Flavobacterium*, *Achromobacter*, to that of Gram-positive species, such as *Micrococcus*, to that of the most radiation tolerant of the yeasts. Consequently, such yeasts may survive low dose irradiation if present at high enough numbers initially (Corlett, 1967), though with no public health significance since no yeasts are important in food poisoning.

During the irradiation of sausage meat, the main yeasts that survived were *Candida zeylanoides*, *Debaryomyces hansenii*, *Trichosporon cutaneum* and *Sporobolomyces roseus* (McCarthy and Damoglou, 1996). Their survivor curves varied from sigmoidal to exponential and depended on the irradiation menstruum, i.e. whether *meat* or phosphate buffer. As a result of the extensive shoulder on some of the survivor curves, doses as high as about 5 kGy were required to achieve a reduction in numbers of 1 log in some instances (e.g. *Tr. cutaneum*).

The high radiation tolerance of some such yeasts may allow them to survive in some irradiated foods and replace *bacteria* to become the major, though safe, spoilage flora. This has been observed, for example, in certain *seafoods* that have been given doses above about 3 kGy, then stored in air at 0.6 to 5.6°C (Eklund *et al.*, 1965). The largest number of isolates from 4 kGy-irradiated and chill-stored crabmeat were strains within the genera *Cryptococcus*, *Trichosporon*, *Torulopsis* and *Rhodotorula*. If air is excluded, e.g. by vacuum or modified atmosphere packaging, then lactic acid *bacteria* tend to outgrow any surviving yeasts and constitute the eventual spoilage flora (Licciardello *et al.*, 1967).

See also Microorganisms – relative resistances.

References

Corlett, D.A. Jr (1967) Microbial selection due to ionizing radiation, *Food Technology*, **21**, 755–801.

Eklund, M.W., Spinelli, J., Miyauchi, D. and Dasson, J. (1965) Development of yeast in irradiated Pacific crab meat, *Journal of Food Science*, **31**, 424–31.

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McCarthy, J.A. and Damaglou, A.P. (1996) The effect of substrate on the radiation resistance of yeasts isolated from sausage meat, *Letters in Applied Microbiology*, **22**, 80–4.

Stehlik, G. and Kaindl, K. (1966) Microbiological studies on the influence of combined processes of heat and irradiation on the survival of *Saccharomyces cerevisiae* var. ellipsoideus, in *Food Irradiation*, International Atomic Energy Agency, Vienna, pp. 299–305.

Yersinia

General

Yersinia enterocolitica is a Gram-negative pleomorphic rod-to-ovoid shaped bacterium. It is widespread in the environment but principal sources of the organism, which lead to food contamination, are the oral cavity and gastrointestinal tract of pigs. *Y. enterocolitica* is reasonably salt tolerant, growing in 5% but not 7% NaCl, and is psychrotrophic, being capable of slow growth at temperatures as low as 0°C. Atypical *Y. enterocolitica*-type organisms (e.g. *Y. intermedia*, *Y. frederiksenii* and *Y. kristensenii*) are thought to be non-pathogenic. Many strains of *Y. enterocolitica* isolated from foods are likewise avirulent. Virulent strains harbour a virulence-associated plasmid that controls the production of antigens, which allow the *micro-organisms* to grow intracellularly after phagocytosis by macrophages.

Radiation resistance

The tolerance of *Y. enterocolitica* to *ionizing radiation* is very low, probably less than that of *Campylobacter* and *Aeromonas* species. For example, the *D-value* of *Y. enterocolitica* was found to be only about 0.10 kGy in γ-irradiated uncooked beef at 18°C (Tarkowski *et al.*, 1984).

Reference

Tarkowski, S.C. Stoffer, C.C., Beumer, R.R. and Kampelmacher, E.H. (1984) Low dose gamma irradiation of raw meat. 1. Bacteriological and sensory quality effects in artificially contaminated samples, *International Journal of Food Microbiology*, **1**, 13–23.

Yoghurt *see* Dairy products.

Entries

Main entries in bold typeface.

Spices
Spores – sensitization to heat
Squash
Staphylococcus aureus
Starch
Starfruit, *see* Carambola
Sterilization
Stone fruits, *see* Apricot; Cherry; Nectarine: Peach; Plum
Strawberry
Sugar
Supercooling
Sweetcorn
Sweet potato
Sweet potato wine, *see* Wine
Synergism

Taenia, *see* Parasites
Tangerine, *see* Orange
Tapeworm, *see* Parasites
Temperature
Temperature rise
Texture
Thermoluminescence
Thiamine
Tocopherols (vitamin E)
Tomato
Toxicology
Toxins
Toxoplasma, *see* Parasites
Trace elements, *see* Minerals and trace elements
Tragacanth gum, *see* Gums
Trichina, *see* Parasites
Tropical and subtropical fruits
Tubers, see Artichoke – Jerusalem; Potato; Sweet potato; Yam
Turkey
Turnip
o-Tyrosine

Unique radiolytic products (URPs)

Vegetables, *see* Fruit and vegetables; Vegetables – dried; Vegetables – cut, prepacked
Vegetables – dried
Vegetables – cut, prepacked
Vibrio
Viruses
Viscometry
Vitamin A, *see* Retinol
Vitamin B1, *see* Thiamine
Vitamin B2, *see* Riboflavin
Vitamin B5, *see* Niacin
Vitamin B6, *see* Pyridoxine
Vitamin B10, *see* Biotin
Vitamin B12, *see* Cyanocobalamin
Vitamin C, *see* Ascorbic acid
Vitamin D, *see* Calciferol
Vitamin E, *see* Tocopherols
Vitamins
Volatiles

Walnut, see Nut
Water, *see* Ionization
Water activity
Wheat, *see* Cereal grains; Cereal products; Immune response; Polyploidy
WHO (World Health Organization), *see* FAO/IAEA/WHO
Wholesomeness
Wine

Xanthan gum, *see* Gum
X-rays

Yam
Yeasts
Yersinia
Yoghurt, *see* Dairy products

Entries by category

Main headings

Biological

Anisakis, *see* Parasites

Bacteria *see* Aeromonas; Campylobacter; Clostridium botulinum; D-value; Escherichia coli; Lactobacillus; Listeria; Micro-organisms – relative resistances; Micro-organisms – safety; Pseudomonas; Salmonella; Shigella; Spores – sensitization to heat; Staphylococcus aureus; Toxins; Vibrio; Yersinia

Caribbean fruit fly, *see* Insects
Climacteric, *see* Ripening and senescence
Codling moth, *see* Insects; Insect disinfestation
Coleoptera, *see* Insects

Flatworm, *see* Parasites
Fruit fly, *see* Insects; Insect disinfestation

Insects

Lepidoptera, *see* Insects
Liver fluke, *see* Parasites

Mango seed weevil, see Insects
Mediterranean fruit fly, see Insects
Melon fruit fly, *see* Insects
Micro-organisms
Mites, *see* Insects; Insect disinfestation
Moulds

Nematode, *see* Parasites

Oriental fruit fly, *see* Insects

Pigment, *see* Colour
Parasites

Ripening and senescence

Queensland fruit fly, *see* Insects

Taenia, *see* Parasites
Tapeworm, *see* Parasites
Texture
Toxoplasma, *see* Parasites
Trichina, *see* Parasites

Yeasts

Detection methods

Carbon monoxide
Chemiluminescence
Conductivity, *see* Impedance and conductivity
Cyclobutanone, *see* Detection; 2-Dodecylcyclobutanone
DEFT, *see* Direct epifluorescent filter techniques
Detection
Direct epifluorescent filter technique
DNA damage
2-Dodecylcyclobutanone

Electron spin resonance
ESR, *see* Electron spin resonance

Hydrocarbons, *see* Volatiles
Hydrogen

Identification of irradiated foods, *see* Detection
Impedance and conductivity

Photostimulated luminescence

Supercooling

Thermoluminescence
o-Tyrosine

Viscometry
Volatiles

Food components

Additives
Alginate
Amino acids, *see* Proteins
Antioxidants, *see* Additives

Biotin

Calciferol
Carob gum, *see* Gums
Carbohydrates
Carotene, *see* Retinol (vitamin A)
Carrageenan
Cellulose, *see* Pectin and cellulose
Chlorophyll, *see* Colour; Potato
Cholecalciferol, *see* Calciferol

Dehydroascorbic acid, *see* Ascorbic acid

Enzymes

Fats, *see* Lipids; Volatiles
Fatty acids, *see* Lipids
Folic acid
Food components

Gelatin
Gelling agents, *see* Agar; Alginate; Carrageenan; Gelatin; Pectin and cellulose
Gluten, *see* Cereal products
Guar, *see* Gums

Food products

Dried foods
Dried fruit
Dried vegetables, *see* Vegetables – dried

Eggplant, *see* Aubergine
Eggs – dried
Eggs – fresh
Endive

Fatty foods
Feeds, *see* Animal diets
Figs
Figs – dried, *see* Dried fruit
Fish
Fish – dried
Flour, *see* Cereal grains; Cereal products
Frog Legs
Frozen foods, *see* Direct and indirect action of ionizing radiation
Fruit juice, *see* Juice
Fruit and vegetables

Garlic
Ginger
Grain, *see* Cereal grains
Gram, *see* Legume
Grape
Grape must, *see* Wine
Grapefruit
Groundnut, *see* Nut
Guava

Ham, *see* Meat; Nitrite reduction
Herb, *see* Spice
Herbal teas
Hospital diets, *see* Sterilization

Juice

Kiwifruit

Lamb, *see* Meat
Legume
Lemon
Lentil, *see* Legume
Lettuce
Lime
Longan
Lychee

Maize, *see* Cereals; Sweetcorn
Mango
Mangosteen
Meat
Melon
Milk, *see* Dairy products
MSM (mechanically separated poultry meat), *see* Poultry
Mushroom
Mutton, *see* Meat

Nectarine
Nut

Oats, *see* Cereal grains; Vitamins
Oilseeds, *see* Legumes
Okra
Olive
Onion
Orange

Papaya
Pasta, *see* Cereal products
Pea
Peach
Peanut, *see* Nut
Pear
Pepper, *see* Capsicum; Spices
Persimmon
Pet foods, *see* Animal diets
Pineapple
Pinenut
Pistachio
Plum
Pome fruit, *see* Apple; Pear
Pork, *see* Meat
Potato
Poultry
Prawn, *see* Shrimps and prawns
Prunes, *see* Dried fruit
Pulse, *see* Legumes

Raisin, *see* Dried fruit
Rambutan
Raspberry, *see* Berry
Ready meals
Rice

Sapota
Sausage, *see* Meat
Seafood
Seasonings, *see* Spices
Shallot, *see* Onion
Shellfish, *see* Seafood; Shrimps and prawns
Shrimps and prawns
Soya bean, *see* Legumes
Soya sauce
Spices
Squash
Starfruit, *see* Carambola
Stone fruits, *see* Apricot; Cherry; Peach; Nectarine; Plum
Strawberry
Sweetcorn
Sweet potato
Sweet potato wine, *see* Wine

Tangerine, *see* Orange

Tomato
Tropical and subtropical fruits
Tubers, *see* Artichoke – Jerusalem; Potato; Sweet potato; Yam
Turkey
Turnip

Vegetables, *see* Fruit and vegetables; Vegetables – cut, prepacked; Vegetables – dried
Vegetables – cut, prepacked
Vegetables – dried

Walnut, *see* Nut
Wheat, *see* Cereal grains; Cereal products; Immune response; Polyploidy
Wine

Yam
Yoghurt, *see* Dairy products

Microbiological

Adenovirus, *see* Viruses
Aeromonas
Aflatoxin, *see* Moulds
Alternaria, *see* Moulds
Aspergillus, *see* Moulds

Bacteria *see* Aeromonas; Campylobacter; Clostridium botulinum; D-value; Escherichia coli; Lactobacillus; Listeria; Micro-organisms – relative resistances; Micro-organisms – safety; Pseudomonas; Salmonella; Shigella; Spores – sensitization to heat; Staphylococcus aureus; Toxins; Vibrio; Yersinia
Botrytis, see Moulds
Bovine spongiform encephalopathy, *see* BSE
BSE
Botulism, *see* Clostridium botulinum

Campylobacter
Cholera, *see* Vibrio
Clostridium botulinum – General
Clostridium botulinum – proteolytic, types A and B
Clostridium botulinum – non-proteolytic, types B and E
Cocksackie virus, *see* Viruses

D-value

Echovirus, *see* Viruses
Enterobacteriaceae, *see* Escherichia coli; Salmonella; Shigella
Enterococcus, *see* Lactobacillus
Escherichia coli

HACCP
Hazard analysis and critical control point, *see* HACCP
Herpes simplex virus, *see* Viruses
Influenza virus, *see* Viruses

Lactobacillus
Listeria

Micro-organisms – relative resistances
Micro-organisms – safety
Modelling
Moulds
Mycotoxins, *see* Moulds

Newcastle disease virus, see Viruses

Penicillium, *see* Moulds
Poliovirus, *see* Viruses
Predictive modelling, *see* Modelling
Prions, *see* BSE
Pseudomonas

Rhizopus, *see* Moulds

Salmonella
Sensitizers
Shigella
Simian virus, *see* Viruses
Sous vide
Spores – sensitization to heat
Staphylococcus aureus

Toxins

Vibrio
Viruses

Yeasts
Yersinia

Physical

Becquerel
Caesium-137, *see* Radionuclide
Cobalt-60, *see* Radionuclide
Curie

Density, *see* Dose distribution; Facilities
Direct and indirect action of ionizing radiation
Dose
Dose distribution
Dose rate
Dose uniformity, *see* Dose distribution
Dosimeter

Electromagnetic spectrum
Electron
Electron accelerator, *see* Facilities
Electron beam machine, *see* Facilities
Electron spin resonance
Electron volt

Equilibrium relative humidity, *see* Water activity
Equipment, *see* Facilities
ESR, *see* Electron spin resonance

Facilities
Free radical

Gamma radiation, *see* Gamma rays; Facilities
Gamma rays
Gray
G-value

Half-life
Heat, *see* Combination treatments; Sensitization of spores to heat
Hydrogen peroxide
Hydrogen radical
Hydroperoxyl radical

Indirect action, *see* Direct and indirect action of ionizing radiation
Induced radioactivity
Ionization
Ionizing radiation
Isotope, *see* Radionnuclide

Overall average dose, *see* Dose distribution
Overdose ratio, *see* Dose distribution
Oxygen

Rad
Radioactivity
Radioisotope, *see* Radionuclide
Radiolytic product
Radionuclide
Re-irradiation
Rem
Rep
Roentgen

Safety of irradiation facilities
Shielding, *see* Facilities; Safety
Sievert

Temperature
Temperature rise

Water activity

X-rays

Toxicological

Ames test

Benzo (α) pyrene quinone

Direct and indirect action of ionizing radiation

Formaldehyde
Free radical

Hydrogen peroxide
Hydrogen radical
Hydroperoxyl radical

Immune response
Induced radioactivity
Injury

Mutagens
Mutations

Pesticide
Polyploidy

Radiolytic product

Toxicology
Toxins

Unique radiolytic products