

Irradiation Applications in Dairy Products: a Review

Oluwakemi B. Odueke¹ · Karim W. Farag² · Richard N. Baines¹ · Stephen A. Chadd¹

Received: 6 March 2015 / Accepted: 29 February 2016 / Published online: 7 March 2016
© Springer Science+Business Media New York 2016

Abstract The demand for raw and fresh dairy products with the desired organoleptic characteristics and health benefits led to research in non-thermal processing technologies aiming to retain all the product qualities and nutrients. Irradiation is an emerging non-thermal technology used in destroying micro- and macroorganisms that might exist in food by exposure to either gamma (γ) rays from radioactive isotopes (cobalt⁶⁰ or caesium¹³⁷) or an electron accelerator (electron beam or X-radiation) under a controlled environment. With the endorsement of many international food and health organisations such as the Food and Agriculture Organization (FAO) and World Health Organization (WHO), irradiation is becoming more widely researched as a process to maintain quality, improve safety and reduce quarantine and post-harvest loss. Irradiation has the potential for allergenicity reduction and the provision of a sterile diet for immunocompromised patients. Unlike other food categories, the use of irradiation as a preservative technique on dairy products has received little attention due to the complexity of the product varieties. Whilst being accepted in some countries, the adoption of irradiation as an alternative measure of treating and preventing potential problems in the food chain faces strict opposition in many countries. In this review, the focus is on the radiation processing as an emerging technology and its specific application on dairy products.

Keywords Food irradiation · Dairy · Food safety · Allergenicity · Non-thermal preservation

Introduction

Food safety is of global concern with dire consequence on human health and the environment if not adequately maintained leading to economic loss and potentially human life. The need for food safety is therefore paramount with ongoing globalisation of food supply resulting in advanced and novel preservation methods. Food processing is a synergetic approach involving physical methods in transforming raw plant/animal materials into handy products. In the present day, the food industry is expected to avoid or prevent undesirable changes in food quality to provide a wide variety of organoleptic favoured food. Also expected of the industry in satiating the requirements of a wide demographic within different cultures are the development and adaptation of new food processes. Alongside the shelf-life, consumers now judge food quality based on its nutritional and sensorial characteristics (Norton and Sun 2008). Food preservation techniques have mainly been focused on the need to inhibit microbial growth and increase the shelf-life of foods without compromising quality and safety (Lee 2004). Over the years, several food preservation techniques have been used, adopted and accepted by the industries and consumers: smoking, salting, curing, drying and pasteurisation. These techniques, however, aside from eliminating food spoilage microorganism often have limitations associated with them especially modification to the organoleptic properties and nutrient deficits.

In contrast, high hydrostatic pressure (HHP), pulsed electric fields (PEFs), ultrasound (US), irradiation and cold plasma (CP) are emerging technologies that have already found application in the food industry and related sectors.

✉ Karim W. Farag
kfarag@harper-adams.ac.uk

¹ School of Agriculture, Food and Environment, Royal Agricultural University, Cirencester, UK

² Department of Food Science and Agri-Food Supply Chain Management, Harper Adams University, Newport, UK

Substantial research has undergone to understand the impact of these non-thermal technologies on biological cells, enzymes and food constituents (Barros-Velazquez 2011; Knorr et al. 2011).

Food irradiation has the ability to disrupt the microorganism DNA thereby prolonging shelf-life and enhancing food safety without detrimental effect on the sensorial and nutritional quality when applying the appropriate dose (McNulty 1988; World Health Organization 1999; Molins 2001; Diehl 2002); this has led to increased application of ionising radiation worldwide.

According to Kaferstein (1990), the full association of WHO and FAO to food irradiation processing can be justified based on the beneficial effect of the process in the provision of quality and safer food to mankind. WHO (1994) acknowledged the effectiveness of food irradiation in ensuring safety and extending shelf-life without quality deterioration and thus encouraged the use of the technique for combating food losses and foodborne illness. The food irradiation process has two major advantages:

- (i) Annihilation of food microbes resulting in production of safer foods
- (ii) Food shelf-life prolongation through killing of pests and delaying the deterioration process thus curtailing waste and leading to increase in food supply (Diehl 1985)

Furthermore, irradiation is being used for animal feed decontamination, sterilisation of food for immune-compromised patients needful of sterile diets and in medicine for diagnosis and treatment, sterilisation of equipment and for modification and improvement of the physical properties of polymeric materials (Kilcast 1994; Kume and Todoriki 2013). Tables 1 and 2 show some of the potential benefits food irradiation could realise and the dose range used in some applications.

Several comprehensive reviews have been written on irradiation application, safety and effect on food products. A review on the safety of food irradiation was authored by Crawford and Ruff (1996), whilst Farkas (1998) documented the feasibility of irradiation as a viable technology in decontaminating food and reducing foodborne illnesses. Other relevant research endeavour included effects on food vitamins (Dionísio et al. 2009), meat flavour (Brewer 2009),

safety and quality of poultry and meat products (O'Bryan et al. 2008) and detection and impacts on fish and seafood shelf-life (Arvanitoyannis et al. 2009) which reflect the amount of work done and published on several food classes. Also published are irradiation use in phytosanitary applications (Hallman 2011); post-harvest disease control through the sole use of irradiation, in combination with other technology (Temur and Tiriyaki 2013); and its effects on phytochemicals and antioxidants in plant produce (Alothman et al. 2009). Whilst protein foods generally and their chemical changes from the application of the technology have been the subject of many studies, fewer were on dairy products possibly due to reported organoleptic degradation associated with high-dose treatment. The focus of this study is to review the use of irradiation technology for dairy products.

Food Irradiation Technology—Overview

Principles of Irradiation

Food irradiation involves the exposure of bulk or pre-packaged food to ionising radiations sourced from either accelerators that produce controlled amounts of X-rays, high-energy electron beams (β particles) or gamma (γ) rays from radioactive isotopes of cobalt (^{60}Co) or caesium (^{137}Cs) in a controlled environment, as shown in Table 3. All three types of radiation result into the excitation of the atoms in the target food product, but the energy is limited and does not interact with the nuclei to prompt radioactivity (Grandison 2012). However, ionising radiation has a detrimental impact on microorganisms in food if applied at a specific dose. The energy from the ionising radiation inactivates microorganisms by damaging the critical element in the cell mostly the chromosomal DNA (Steele 2001). The damage prevents multiplication and arbitrarily terminates most cell functions. The damage to the DNA results from direct collision between radiation energy and the genetic material or as a result of the interaction between an adjacent molecule which in most situations is a water molecule and the radiation energy which then reacts with the DNA (Fan and Sommers 2013).

The efficiency of a radiation dose depends both on the food composition and external factors like presence or absence of

Table 1 Some of the benefits in relation to food irradiation

Benefits to consumer	Benefits to wider environment
Control spoilage	Less spoilage in transit and so lower costs
Eliminate pathogens causing foodborne diseases	More efficient food supply
Delay ripening and sprouting	Potential reduction in cold storage needs
Extension of storage	Less use of fumigation
Increase trade in food products globally	
Better choice of safe to eat 'exotic' foods (e.g. rare-cooked meats)	

Table 2 Irradiation dose ranges and food applications (adapted from Roberts 2014; Arvanitoyannis and Tserkezou 2010)

Dose range (kGy)	Example applications
Less than 1	Inhibit sprouting in potato, onion and garlic Delay ripening in bananas Pest disinfection in fresh produce, dried foods Parasite inactivation in pork (trichinella) Increase the yeast population in soft cheese
1–10	Reduce spoilage organisms in strawberries, mushrooms, dried fish Reduce non-sporulating pathogens in meats, shellfish, spices Extend storage for infant milk
More than 10	Reduce pathogens to point of sterility in spices; hospital diets, emergency rations Inhibit <i>Enterobacter sakazakii</i> growth in milk powder without affecting the nutrients or flavour

oxygen, moisture content, density and temperature. Irrespective of the absorbed dose, irradiation is indeed a low energy process where at a high-dose range, product temperature increases by few degrees centigrade (Pryke and Taylor 1995; Hallman 2011). It is, however, worth noting that irradiated foods are not radioactive since the absorbed energy (below 5 and 10 MeV for gamma (γ) rays energy and electron energy, respectively) is not sufficient to affect the neutrons in the nuclei of the food molecules (Mahapatra et al. 2005; Aquino 2012).

Gamma (γ) Rays

In theory, it is regarded as the simplest form of irradiation, and photons are emitted by radioactive isotopes of cobalt (^{60}Co) or caesium (^{137}Cs). The photons are relatively higher in frequency and hence energy in comparison to X-ray photons. Penetration depth can be several feet and can target microorganisms anywhere within that range. Even though gamma (γ) rays can be simple in concept, in practice, it could be more challenging. The radioactive isotopes are produced by exposing them to a nuclear reactor core, and even after the source is selected, logistically, the exercise is complicated as the source cannot be switched off. Moreover, they do not come with directional or intensity controls. To contain gamma (γ) rays,

the source is usually immersed in water and insulated by several layers of concrete as shown in Fig. 1 (Prejean 2001).

Electron Beam

High-energy electron beams are produced in an electron gun, and it is easier to direct the electrons using a magnetic field. The word ‘irradiation’ in this case could be misleading as food is not exposed to electromagnetic radiation or beta rays, but the process has a similar impact to gamma (γ) rays irradiation. Shielding during the process is still necessary but not to the extent of gamma (γ) rays where concrete bunkers are used. The main drawback of the e-beam is its penetration depth, and it is limited to about an inch which limits its application to many foods as shown in Fig. 2 (Prejean 2001; Berejka and Larsen 2014).

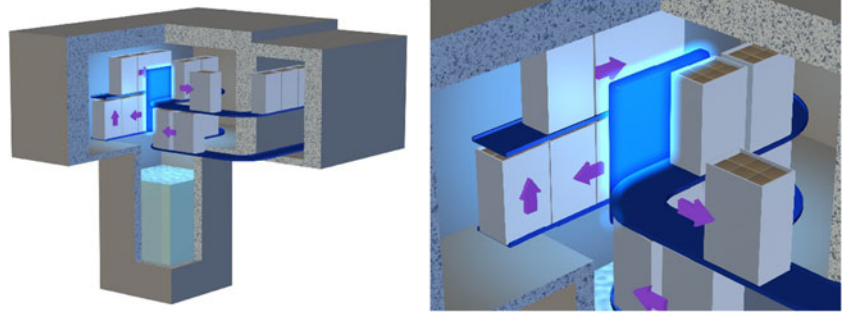
X-rays

Relatively a new technique, it involves exposing food to high-energy photons which potentially have a deeper penetration depth than gamma (γ) rays. The radiation can be switched on and off which is a big advantage, yet when it is ‘on’, shielding is necessary but again not to the extent of gamma (γ) rays. The

Table 3 Sources of ionising radiation (adapted from Berejka and Larsen 2014)

	Electron beams	X-rays	Gamma rays
Power source	Electricity	Electricity	Radioactive isotope (^{60}Co or ^{137}Cs)
Properties	Electrons	Photons ($\lambda = 3 \times 10^{-10}$ m)	Photons ($\lambda = 1 \times 10^{-12}$ m)
Emissions	Unidirectional	Forward peaked	Isotropic (direction cannot be controlled)
Maximum penetration	38 mm from 10 MeV	~400 mm	~300 mm
Dose rate	100 kGy/s	0.27 kGy/s	2.8×10^{-3} kGy/s

Fig. 1 Gamma radiation process at Synergy Health, now part of STERIS in Swindon, UK



process does not result in any radioactive substances or by-products (Prejean 2001).

immediately distributed into the food supply chain post-application.

Comparison to Other Techniques

Food irradiation is one of the many techniques used in processing food, but it has a number of practical benefits and unique selling proposition (USP) as described by Roberts (2014). It is a multipurpose technology addressing a number of issues such as food safety, food security and trade (biosecurity). Food irradiation has a broad-spectrum effectiveness and efficiency against all non-spore-forming bacteria and against insects and many other pests. Thermal processing of food can have a detrimental impact on food quality, and this is an issue avoided when using irradiation as it is a cold process. The food products can be treated in their final packaging due to the benefit of penetration depth. Microorganisms are not protected by the position or shape of the packaging, and it is a substantial advantage for this technology to be capable of treating pallet loads if required. The food product being solid or raw can be treated. Chemicals or chemical residues are not used in this treatment. Food irradiation is considered as a relatively easy to control process (usually dependent only upon conveyor speed and the power/activity of the radiation source), and finally, treated food can be

Dairy Products

Dairy products are consumed daily by millions of people around the world for nutrient enrichment. However, a product's functional and storability properties can be altered by the application of processing technologies. The consumption of dairy products over decades has been an integral element of the human diet. Milk is regarded as an important part of the balanced diet owing to its power of sustenance in all stages of development. The nutritional importance of milk molecules as a source of quality proteins and energy-rich fat has been well researched. It is also known to contain important micronutrients like vitamins, potassium, magnesium, calcium and sodium vital for general development of the human body. However, in its natural state, milk is highly susceptible to rapid spoilage by the action of naturally occurring enzymes and microbes. These spoilages occur by the existence of a neutral pH and high water content encompassing a wide range of nutrients such as protein, carbohydrates, vitamins, fats and minerals, and they serve as a suitable growth medium for microorganisms either desirable or undesirable (Perko 2011). Lactic acid bacteria (LAB), a technologically important microbe, is present in raw milk which is highly desirable in cheese production alongside pathogenic and spoilage bacteria.

Food safety is of global priority with millions of foodborne illnesses and often death reported every year resulting from the consumption of unsafe food. Every continent over the past decade has documented serious outbreaks of foodborne disease, whilst the rates of illnesses in many countries are increasing significantly. Hence, safety is a critical issue in the availability of wholesome food crucial to ensuring a healthier population.

Dairy Irradiation

Milk and milk products are essential elements in the food chain. The food industry uses vast amount of liquid and

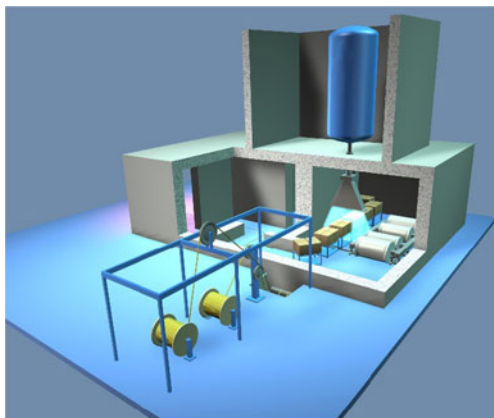


Fig. 2 Electron beam radiation process at Synergy Health, now part of STERIS in Swindon, UK

powdered milk, concentrated milk, creams and butter as raw materials for further processing, whilst the consumers use milk for cooking and beverages. Microbial contamination occurs at different stages of procurement (cow's udder), processing (added ingredients) and distribution. Pathogens such as *Listeria monocytogenes*, *Salmonella* species and *Staphylococcus aureus* have all been causes of major foodborne outbreaks (Yagoub et al. 2005). Pasteurisation has been used effectively in sterilising milk over decades. However, of great concern to the dairy industry are the psychrotrophic microorganisms due to their capability to develop resistance with the ability to produce heat-resistant proteolytic and lipolytic enzymes at refrigerating temperature due to post-pasteurisation contamination (Cousin 1982).

Due to the economic crunch and the quest for greener technologies, conclusive sterilisation of dairy products is crucial as pathogens have become a major issue in the industry. These necessitate the research into emerging technologies of non-thermal processing with the ability to retain quality and nutrition (Knorr 1999; Farag et al. 2008, 2011) and also because of the human fondness for the consumption of raw dairy products due to preferred sensory properties (Buchin et al. 1998). Irradiation is one non-thermal technology that has generated both controversial and considerable research curiosity for the treatment of food over the last few decades (Pryke and Taylor 1995). There is slow adoption in the irradiation of dairy products due to the effective elimination of pathogens by heat pasteurisation. Reports about development of off-flavours in irradiated dairy products also hindered the use of the process, though this has been contradicted by research concluding that irradiating at low doses and/or in frozen conditions can be an effective treatment without compromising the organoleptic properties (Hashishaka et al. 1990a, b; Bougle and Stahl 1994). However, success in the improvement of microbial quality of dairy products by gamma irradiation has been reported by Bandekar et al. (1998), Bougle and Stahl (1994), Ennahar et al. (1994) and Hashisaka et al. (1989). Furthermore, the use of electron beam irradiation in the enhancement of sensory, nutritional and microbial properties whilst inactivating spoilage microorganism in mozzarella cheese was reported by Huo et al. (2013). Officially, in France and Czech Republic, casein and caseinates are cleared for irradiation at a maximum dose of 3 kGy for microbial control, whilst in Croatia, dried milk products are permitted at a maximum dose of 3 kGy for disinfestation and 30 kGy for microbial control (IAEA 2012).

Cheese

Cheese is a dairy product derived from the milk of cows, goats, sheep or buffalo. Cheese which is a good source of protein, calcium, phosphorus and vitamin B₁₂ is produced by acidification of milk and the addition of the enzyme rennet

which causes coagulation of the milk protein casein. After coagulation, the curds which are the solid bits are separated and pressed into its final form. Cheeses both hard and soft are produced in a wide range of textures, flavours and styles depending on the origin of milk, animal diet, butterfat content, raw/pasteurised milk, type of processing and ageing. Cheeses, like mature cheddar, are aged for up to a year or longer before they are ready to eat. In the UK for example, there are hundreds of varieties of cheeses produced. Cheese is prized for its extended shelf-life, portability, high fat content and nutrient value. Cheese unlike milk is more dense with a long shelf-life though for how long depending on the type of cheese. In the process of cheese ageing and storage at low temperature, mould growths often arise resulting in loss through trimmings or total discard. In addition to the loss, there is the potential for the production of carcinogenic and toxic metabolites from certain moulds (Blank et al. 1992); thus, inhibiting the growth of moulds and other food poisoning microorganisms is paramount to human health. Investigations into the suitability of applying irradiation as a preservation technique on various dairy products, such as cheese (Blank et al. 1992; Bougle and Stahl 1994; Hashisaka et al. 1989, 1990a; Huo et al. 2013; Tsiotsias et al. 2002), ice cream (Hashisaka et al. 1989) and yoghurt (Hashisaka et al. 1990a), have been conducted. These studies highlight the advantage of packaging the product before treatment thus eliminating post-treatment contamination in addition to microbial contamination (Blank et al. 1992).

Research by Blank et al. (1992) documented that cheese inoculated with *Penicillium cyclopium*, irradiated at 10 °C with a dose of 0.21 and 0.52 kGy, exhibited a shelf-life of 15 and 17.5 days, respectively, showing an approximate extension of 3 and 5.5 days. On the other hand, cheese inoculated with *Aspergillus ochraceus*, under the same treatment and conditions, has a shelf-life of 65 and 74 days, respectively, showing an extension of approximately 41.5 and 50.5 days correspondingly when compared with the control. Increase in treatment from 0.52 to 1.15 kGy showed growth inhibition for up to 98 days at both 10 and 15 °C. Furthermore, when the cheese inoculated with *P. cyclopium* spore was increased 10-fold (500 spores/cm² per surface) at 1.2 kGy, it demonstrated a shelf-life of 52.5 days at 10 °C in comparison with the control signifying an extension of 44.5 days which is half the extension time acquired with cheese containing 1-fold (50–60 spores/cm²) per surface. Whilst at increased temperature of 15 °C, the shelf-life was only increased by 3 days. On the contrary, cheese inoculated with 10-fold *A. ochraceus* showed a shelf-life of 107 days irrespective of the storage temperature. With reference to the average *D*₁₀ value (0.213 kGy) of *A. ochraceus*, *P. cyclopium* spores are more radiation resistant than *A. ochraceus* spores. Blank et al. (1992) thus concluded that irradiation as a tool in enhancing shelf-life of vacuum-packaged cheddar cheese depends mostly on the nature of

contaminant, applied dose and post-irradiation storage temperature with the latter being the most crucial from the microbiological and public health perspective.

Tsiotsias et al. (2002) in their study on soft whey cheese at doses of 0.5, 2.0 and 4.0 kGy at 4 °C reported the absence of moulds and *Enterobacteriaceae* in the irradiated samples, whilst there was a reduction in yeast population which was later detected during storage. At both 2.0 and 4.0 kGy, there was reduction in the microbial load of aerobic mesophilic bacteria by approximately 1 and 2 log cycles. The recorded D_{10} value for *Listeria monocytogenes* was 1.38 kGy which correlates with an earlier study by Hashisaka et al. (1989). This value according to the authors may be due to the composition of the food product studied whilst noting that radiosensitivity of bacteria varies with the medium in which the process occurred. The control of *L. monocytogenes* following 28 days of storage at 4.0 kGy without any detrimental effect on the quality and the sensorial attributes were further established by the authors.

Huo et al. (2013) investigated the efficiency of electron beam irradiation as a complementary preservation method in the shelf-life extension of mozzarella cheese ripened at 10 °C for 30 days. The ripened cheese was then subjected to five different doses in 10 MeV electron beam accelerator at 30 °C. Treated cheeses were subsequently stored at 10 °C for 90 days to speed up the deterioration process whilst the sensory and microbial analysis was assessed.

In the irradiated samples, there was no detection of coliform, moulds and yeast implying the inhibition of microorganisms by electron beam irradiation. Also reported was the irradiation influence on the maximum cell load attained at the stationary phase by *Pseudomonas* sp. alongside the lag time prolongation against varying irradiation doses. The reduction in the attained maximal cell load at the stationary phase was linked to the significant shelf-life extension compared to the control. According to the study, increased irradiation doses significantly increased the shelf-life of the product resulting in the inhibitory effect of high-dose samples than the low-dose samples.

In the sensory analysis, slight variations were observed in the different irradiation doses supporting the hypothesis that irradiation doses of <2 kGy do not deteriorate the sensory properties of cheese. The texture was maintained whilst there was alteration in the odour when irradiated to 1.51 and 2 kGy. However, at 2.5 kGy, the sensory attributes reported were bitter, oxidation flavour, candle-like odour, rancid odour and strong oxidised odour.

Furthermore, the baking test analysis showed no difference in the tensile stretching, oil-off and melting properties between the treatment and control. The authors recorded the efficiency of electron beam irradiation at a dose of 2 kGy in the inhibition of microorganisms without compromising the sensory qualities of cheese.

The acceptability from a health point of view of Camembert cheeses manufactured from raw milk treated with doses up to 2.5 kGy of gamma irradiation was documented by SCF (1992) whose main objectives were the reduction of foodborne pathogens and shelf-life extension.

Yoghurt

Yoghurt is a fermented dairy product manufactured with the milk of cows, goats and ewes with its origination linked to the Balkans and the Middle East. It is characterised by a fresh lactic acid smell coupled with a full, pleasant and between slightly and intensely sour taste (Teuber 2000). Yoghurt is considered safe at consumption if avoidable post-pasteurisation treatment is prevented due to the presence of viable content of micro flora of starter cultures and a low pH (Varga 2006). Yoghurt usually has a shelf-life of 3 weeks or less, and the presence of starter cultures, though of health benefit, can compromise the health of immunocompromised patients (Ham et al. 2009). The probiotic effect of yoghurt (Berrocal et al. 2002), the preservative effect of the lactic acid bacteria and low pH could be linked to the insufficient literature on the post-irradiation quality and storage of yoghurt (Ham et al. 2009). Whilst the quality and sensory properties of irradiated plain yoghurt were evaluated at doses of 1, 3, 5 and 10 kGy and stored at refrigerated (4 °C), room (20 °C) and abuse storage temperature (35 °C) (Ham et al. 2009), no difference was found in the total solid, protein content and amino acids of plain yoghurt evaluated. The protein content of the treated plain yoghurt showed no difference either in initial storage time after treatment and after week 3 irrespective of storage temperature. This goes to show that neither the irradiation process nor the storage time and temperature affect the protein content of the plain yoghurt. The lactic acid bacteria count at 3 kGy had about 3-decimal reduction, whilst at 10 kGy, there is an absence of viable cells irrespective of storage temperature and time. The lactic acid bacteria decrease at 4 °C after 2 and 3 weeks of storage in treated samples at doses of 3 and 5 kGy. At room temperature (20 °C) after weeks 2 and 3, the amount of surviving bacteria was significantly reduced when compared with storage at 1 week, whilst at 35 °C, lactic acid bacteria in yoghurt treated at 3 kGy and higher were undetectable, thus indicating the effect of storage temperature on the growth of lactic acid bacteria in plain yoghurt especially in irradiated samples.

The researchers reported that post-irradiated samples stored at the same storage temperature exhibited tendency of reduction in the microbial level. This corroborate an earlier report by Song et al. (2007) that the inability of the bacteria to survive post-irradiation may be due to the lethal effect of the irradiation resulting in damage to the bacteria cells thus preventing division and multiplication which impede adaptation to the environment during storage.

Sensory evaluation 2 h after irradiation showed no significant difference up to a 10-kGy dose. However, evaluation after 1 week at different storage temperatures showed that amongst the sensory attributes evaluated, only the appearance of plain yoghurt irradiated at 3 kGy and above ranked lower than the control at 20 °C storage temperature. The characteristic off-odour associated with irradiation was however not detected with increasing doses which was linked to the fact that the sour taste of plain yoghurt might have concealed the flavour change. Hashisaka et al. (1990a) reported similar sweetness rankings in both the control and irradiated raspberry yoghurt bar when exposed to gamma irradiation dose of 40 kGy at −78 °C which contradicts an earlier report by Hashisaka et al. (1989) where a decrease in the intensity of the sweetness of the irradiated product in comparison to control was documented.

Ham et al. (2009) concluded that irradiating plain yoghurt exhibits the potential to extend the shelf-life, reduces allergenicity and provides a safer product without compromising the chemical and sensory qualities.

Ice Cream

Ice cream is a significant product in the dairy industry and as such is a food product widely sought during summer. The attributed pH, storage period and minimal processing make it liable for microbial growth especially a product from natural origin which sometimes possesses detrimental contaminants likely to cause disease when consumed (Adeil Pietranera et al. 2003). Walker et al. (1990) and Farber and Peterkin (1991) have all documented the occurrence of *Salmonella*, *Yersinia*, *Bacillus cereus* and *Listeria* in ice cream. Irradiation treatment has thus been proven to be efficient in either reducing or eliminating microbial growth in ice cream without affecting the organoleptic properties and the nutritional value (Kamat et al. 2000). Kim et al. (2005) reported the inability to detect *Salmonella Typhimurium* and *Escherichia coli* in chocolate ice cream irradiated at 1 and 3 kGy, respectively. The reported D_{10} values of *E. coli* and *Listeria ivanovii* were 0.28 and 0.77 kGy, respectively, implying the radiation resistance of *L. ivanovii* to be higher in comparison to other pathogens. They also reported the lack of viable cells at 5 kGy dose indicating that irradiating up to 5 kGy may considerably improve the safety of chocolate ice cream.

Kamat et al. (2000) recorded in ice cream treated at 0.38 kGy and −72 °C a higher D_{10} value of *L. monocytogenes* when compared with that at 0.25 kGy and 0 °C signifying a protective effect due to an immobilisation of the free radicals at −72 °C whilst *Yersinia enterocolitica* and *E. coli* were absent. However, a higher D_{10} value for *L. monocytogenes* Scott A was recorded by Hashisaka et al. (1989) at −78 °C in ice cream.

Reduction in microbial count by one log cycle was recorded for 1 kGy at −72 °C in ice cream (chocolate, strawberry and vanilla) with the recorded D_{10} values for *E. coli*, *Y. enterocolitica* and *L. monocytogenes* found to be 0.210, 0.15 and 0.38 kGy, respectively, thus justifying the efficiency of low-dose radiation treatment of ice cream (Kamat et al. 2000). The sensory properties of ice cream treated at above 2 kGy produced off-flavour and aftertaste which was apparent in vanilla ice cream. A slight change in colour and texture was reported by Hashisaka et al. (1990a) when dairy products were exposed to gamma irradiation dose of 40 kGy at −78 °C with characteristic flavour resulting from increased level of off-flavour and a decrease in the overall acceptability. On the contrary, flavours such as peppermint as in the case of peppermint-flavoured ice cream were not affected by the large irradiation dose. It was also observed that the addition of antioxidants prior to treatment and controlled atmosphere packaging influence the preservation of characteristic flavour notes in certain products. It was therefore concluded that a dose of 1 kGy was sufficient in eliminating the number of pathogens present in ice cream (Kamat et al. 2000).

Milk and Edible Coatings

Ziporin et al. (1957) recorded no reduction in the riboflavin, thiamine and niacin levels of powdered milk irradiated at 5 Mrad (50 kGy) at 24 °C. However, the investigation of Ford et al. (1962) on fresh raw milk gamma irradiated at 1 Mrad (10 kGy) under room temperature reported the loss of insignificant amounts of vitamin B₁₂, 60–70 % of riboflavin and 100 % of thiamin. It was concluded that packaging environment has no effect on the recorded vitamin loss.

The application of edible films and coatings by the food industry for shelf-life extension of food (Khwalidia et al. 2004) without being detrimental to the environment necessitates research into the process and composition for better products (Chen 1995; Guilbert et al. 1996; Cieřla et al. 2004). Proteins attributed with good film forming abilities but moderate barrier could be improved structurally by application treatment such as gamma irradiation which is effective in enhancing the functional (barrier and mechanical) properties of edible films produced from caseinate solely or in combinations with other compounds (glycerol), as a plasticizer (Brault et al. 1997; Mezgheni et al. 1998; Vachon et al. 2000; Lacroix et al. 2002; Sabato and Lacroix 2002; Cieřla et al. 2004). Studies showed that cross-linking induced by gamma irradiation was more efficient on caseinates than on whey proteins whose cross-linking thrived better on heating (Vachon et al. 2000; Lacroix et al. 2002). Formation of cross-links occurs in irradiated edible films by the resulting increase in the cohesive force of the protein after treatment.

Brault et al. (1997) studied the effectiveness of gamma irradiation in the production of sterilised edible films from

irradiated milk proteins of both calcium caseinates and sodium caseinate at two concentration levels of 5 and 7.5 % (w/w) with respect to three irradiation doses of 4, 8 and 12 kGy. At 5 % (w/w) concentrations, calcium caseinate solutions treated with doses ranging between 4 and 12 kGy produced significantly more bityrosine. The significant increase in the bityrosine production might be accountable for the observed insolubility in the films obtained from irradiated solution compared to the non-irradiated solutions producing water-soluble films. The differences observed between the calcium and sodium caseinate concentrations with the calcium caseinates higher might be attributed to the formation of more cross-links and enhanced mechanical strength than 5 % (w/w) sodium caseinate solutions. The puncture strength values of the film at the same irradiation dose were reported to be higher in calcium caseinate than in sodium caseinate indicating that it is a function of the two counter ions (calcium and sodium) whilst independent of the irradiation dose and protein concentration. Alternatively, the produced film puncture deformation was documented to be independent of the protein concentration, nature of counter ion and irradiation doses. The authors further demonstrated the improvement in the bityrosine production resulting from addition of plasticizer (glycerol) which was documented as significantly dependent on the irradiation dose and the protein and glycerol concentration. In addition to the above, glycerol addition was found to increase the flexibility of the film alongside mechanical strength enhancement. The beneficial behaviour of glycerol was linked to the preferential binding concept as explained by Gekko and Timasheff (1981). Irradiation, however, was responsible for the toughness and flexibility of the film depending on the concentration (glycerol/protein) ratio. Le Tien et al. (2001) also reported the efficiency of films from irradiated solutions in delaying the oxidation of apples and potatoes whilst also reducing the amount of water loss during storage of strawberries.

A study by Mezgheni et al. 1998 documents the role of gamma irradiation in the creation of bityrosine which is responsible for the cross-links required in the production of edible sterilised film. This result supports an earlier report by Brault et al. 1997 in the formation of edible film based on caseinates. The amount of bityrosine produced was found to be directly proportional to increasing irradiation dose. Also reported was the importance of plasticizers—propylene glycerol (PG) and triethylene glycol (TEG) whose addition significantly increases the cross-link formation and enhanced film flexibility and mechanical strength. The reported efficiency of plasticizer TEG over its counterpart PG was attributed to its chemical structure. Gel formation did not occur in the absence of calcium ions and in un-irradiated samples independent of irradiation dose. However, with the addition of calcium ions,

gels were formed at irradiation doses of 16 and 32 kGy depending on the solution ratio.

According to Cieřla et al. (2004), radiation-induced cross-linking results in the production of protein solution with increased viscosity. The higher viscoelasticity and lower deformation values both demonstrate greater rigidity of the irradiated films. The authors concluded that the functional property of the irradiated samples is significantly different from the non-irradiated samples.

A study by Sabato and Lacroix (2002) on the viscosity of protein-based solutions after irradiation treatment found that at increased irradiation doses, viscosity of solutions containing calcium caseinates with glycerol and soy with glycerol decreases significantly whilst mixtures of whey protein concentrate with glycerol and sodium caseinates with glycerol remained almost constant with sodium caseinates with glycerol exhibiting some form of macromolecule aggregation at 5 kGy. The decrease in the proteins of calcium caseinates and soy could be attributed to the absence of other treatments like thermal which as described by Mezgheni et al. (1998) is essential to induce structural modification within proteins resulting in aggregation of protein solutions.

Advantages of Irradiation on Dairy Products

The growth of psychrotrophic bacteria has been favoured by the rapid cooling and refrigeration of raw milk after collection. However, *Pseudomonas* spp., non-spore forming psychrotrophs, are killed by high-temperature short-time pasteurisation, but their ability to produce heat-stable proteases and lipases which generates off-flavours during the shelf-life stage of pasteurised milk is a greater problem (Perko 2011). The need for monitoring the microbiological quality of raw material by the food industry for the presence of microorganisms with potential spoilage activities is due to the significant losses caused by bacteria spoilage. Proteolytic psychrotrophs are extremely undesirable milk contaminants because of their proteolytic and lipolytic activities. Furthermore, the thermostability characteristic of proteolytic and lipolytic enzymes provides resistance to the thermal process normally used in milk processing which becomes ineffective in destroying them (Perko 2011). Though the somatic cells of proteolytic psychrotrophs are thermally destroyed, the enzymes (proteases and lipases) remain active resulting in the breakdown of protein and fat after pasteurisation of heat-stable proteases and lipases to cause breakdown of protein and fat after pasteurisation (Barbano et al. 2006).

Studies by Dong et al. (1989) reported the retention of riboflavin, thiamine and cobalamin content in dairy products (mozzarella cheese, cheddar cheese, ice cream, yoghurt bars

and non-fat dry milk) treated with gamma irradiation at 40 kGy at -78°C in a nitrogen-modified atmosphere. However, a significant loss in the thiamine content of mozzarella cheese was observed at 0 to 5°C which implies that irradiation of mozzarella cheese at subfreezing temperature helps retain the thiamine content.

Tsiotsias et al. (2002) reported the control of microorganisms by the use of irradiation for soft whey cheese, cheddar cheeses and raw milk Camembert (Hashisaka et al. 1990b; Blank et al. 1992). Irradiation as an instrument in cheese ripening was documented for Ras cheese (Abd El Baky et al. 1986) where the process allegedly accelerated the ripening as a result of increased acid and peroxide values alongside milk coagulation completion time. It was also observed that in comparison to heat pasteurisation, irradiated cheese has improved flavour and enhanced consistency. Seisa et al. (2004) studied the effect of gamma irradiation at different ripening temperatures on the ripening of cheddar cheese whilst monitoring the breakdown of proteins and lipids, microorganism growth and impacts on sensory attributes. The more recent work by Huo et al. (2013) on the effect of electron beam irradiation on the shelf-life of mozzarella cheese found that at a dose of 2 kGy, there was inhibition of spoilage microorganism with insignificant effect on the sensory qualities. The proven effective application of irradiation as a post-packaging decontaminant on dairy products surpasses pasteurisation where post-treatment contamination often arises. Presented in Table 4 are the abbreviated benefits of irradiation on selected cheese and yoghurt products. Judging by previous and ongoing studies, the application of non-thermal preservation techniques such as irradiation could

deliver safe and healthy food with environmental benefits. There is a gap for irradiation application in the dairy sector which due to the complexity of the products has received little attention.

Radiolytic Effect

The irradiation process can result in chemical changes to the proteins within the product as suggested in many studies (Delincee and Ehlermann 1989; Cathalin and McNulty 1996; Elias and Cohen 1977; WHO 1999; Ehlerman 2014). These studies indicated that not only the protein type and structure can be responsible for the changes but also its state (e.g. dry or moist, liquid or frozen). Molins (2001) reported that when proteins were irradiated, large protein molecules were broken down into smaller ones; however, they still resulted in the same amino acids as the original proteins when digested. Minimal changes were reported in total amino acid profile when treated with ionising energy (Arvanitoyannis and Tserkezou 2010). The effects of irradiation on selected dairy products are presented in Table 5.

Legislation

Current UK Legislation

The Food Regulations 1990 legalised the use of irradiation on seven classes of food into the Food Safety Act in the UK in 1991 (Kilcast 1994). The act, however, is subject to

Table 4 Benefits of irradiation on selected cheeses, yoghurts and ice creams

Product	Irradiation type/dose (kGy)	Temp ($^{\circ}\text{C}$)	Benefit	References
Soft whey cheese	Gamma/0.5	4	Slight reduction in aerobic mesophilic bacteria	Tsiotsias et al. (2002)
Soft whey cheese	Gamma/4	4	Absence of moulds and Enterobacteriaceae, yeast reduction and elimination of <i>L. monocytogenes</i> with minimal effect on the sensory qualities	
Raspberry yoghurt	Gamma/40	-78	Sweetness flavour maintained in the presence of nitrogen and helium gas	Hashisaka et al. (1990a)
Strawberry yoghurt bar	Gamma/40	-78	Maintenance of sweet flavour, retention of characteristic fruity flavour in the presence of antioxidant (ascorbyl palmitate) whilst the addition of (BHA/BHT) before treatment	
Vanilla ice cream	Gamma/40	-78	Helium or nitrogen gas packaging maintained the sweet	
American cheese	Gamma/40	-78	Significant difference in the colour of the treated product	
Cheddar cheese	Gamma/40	-78	No effect on the colour	
Mozzarella	Gamma/40	-78	Retention of mouth feel flavour with no significant difference in the texture between control and treated	
Gouda	Gamma/40	-78	Sensorial and textural attributes retained	
Mozzarella cheese	Electron beam	–	Shelf-life extension	Huo et al. (2013)

BHA/BHT butylated hydroxyanisole/butylated hydroxytoluene

Table 5 Radiolytic effect on selected dairy products (adapted from Arvanitoyannis and Tserkezou 2010)

Dairy product	Source (dose in kGy)	Radiolytic effect	References
Milk	Gamma (0, 3, 5 and 10)	Reduction of β -lactoglobulin	Byun et al. (2002)
Milk protein	Gamma (0, 5, 15 and 25)	Increased the viscosity of proteins	Camillo and Sabato (2004)
Baby food (with skim milk powder)	Gamma (0, 0.5, 1.5, 6, 10, 15, 30 and 50)	Increase pf leucine, alanine and glutamine acid Decrease of histidine and methionine	Matloubi et al. (2004)
Soft whey cheese	Gamma (0.5, 2 and 4)	Increased the yeast population	Tsiotsias et al. (2002)
Vanilla, strawberry and chocolate ice cream	Gamma (1, 2, 5, 10 and 30)	Over 2 kGy induced off-odour and after taste in vanilla ice cream	Kamat et al. (2000)

authorisation by the provision of a licence. The protocols covered in The Food (Control of Irradiation) Regulations 1990 outline the process, approved foods and purposes for which it may be used and the conditions that must be fulfilled for granting irradiation licences. Pre- and post-irradiation microbiological standards are a requirement for issuing a licence in the UK (Pryke and Taylor 1995).

This was as a result of a process introduced by the endorsement of the Joint FAO/IAEA/WHO Expert Committee for Food Irradiation (JECFI 1981), that irradiation of food up to an overall average dose of 10 kGy presented no distinct microbiological, nutritional and toxicological threat. The Advisory Committee on Irradiated and Novel Foods (ACINF) was set up by the UK Government to study appropriate scientific data on the safety and wholesomeness of irradiated food. In 1986, the Committee submitted their findings approving the JECFI endorsements (ACINF 1986).

Status of EU and International Legislation

In 12 EU member states, there are a total of 23 approved food irradiation facilities (Belgium, Bulgaria, Czech Republic, France, Germany, Hungary, Italy, Poland, Romania, Spain, Netherlands and the UK) under the governance of Directive 1999/2/EC and Directive 1999/3/EC. Competent authorities in the member states grant approval in accordance with the procedure set out by Directive 1999/2/EC (EFSA 2011). The latter covers general and technical aspects for carrying out irradiation process, labelling and conditions for authorisation.

Directive 1999/3/EC covers the approved foodstuffs and doses. Globally, the application of food irradiation is approved in over 50 countries in a wide variety of foodstuffs with an estimated value of over half a million metric tonnes of food irradiated annually (ICGFI 1999; Lee 2004; Kume et al. 2009; Farkas and Mohacsi-Farkas 2011; Huo et al. 2013). However, the shortcoming experienced in the adoption of irradiation for post-harvest phytosanitary (quarantine) treatment is a result of the international trade agreements. In addition to existing range of products (ground beef, poultry, seafood, spices, herbs and grains) authorised for irradiation, the United States Food

and Drug Administration (USFDA) authorised irradiation as a control measure for foodborne pathogens in spinach and ice-berg lettuce up to a dose of 4 kGy (USFDA 2008).

In 2002, the Scientific Committee on Food (SCF) stated that “as the adverse effects of food irradiation were mostly related to in vitro studies, therefore, it is not appropriate on this basis alone to make a risk assessment on human health in relation to the consumption of 2-alkylcyclobutanones (2ACB) present in irradiated fat containing foods”. Tables 6 and 7 show some of the foods and ingredients of plant and animal origin permitted for irradiation in EU and US countries.

Whilst the joint FAO/IAEA/WHO research on high-dose irradiation (WHO 1999) established that based on the available report, the radiation chemistry, nutritional properties, toxicology and microbiology of food treated with radiation doses above 10 kGy were adequate. The research group also established that foods irradiated at doses sufficient to attain the proposed technical objectives are nutritionally adequate and therefore safe to consume.

Directive 1999/2/EC endorsed food irradiation for the following reasons:

- Reduction in the incidence of foodborne disease through destruction of pathogenic organisms
- Reduction of food spoilage by delaying decay process and destruction of spoilage insects or microorganism
- Reduction of food losses by delaying premature sprouting or germination and ripening
- Disinfestation of plants or plant products of insects (phytosanitary/quarantine treatment)

Limitations of Food Irradiation

The accomplishment of the technical opportunities of food irradiation will only be appreciated if the technology is understood and acknowledged by the consumers. There remains strong opposition to technology connected with the nuclear industry, in contrast to involvements in Belgium and France where food irradiation is not a concern due to the high

Table 6 Sample of foods and ingredients of plant origin permitted for irradiation in the EU and US with doses

Products	Permitted dose (kGy)						
	BE	CZ	FR	IT	NL	PL	US
Deep frozen aromatic herbs	10	10	10	–	–	–	–
Dry or dehydrated spices/seasonings	–	–	–	–	–	–	30
Potatoes	0.15	0.2	–	0.15	–	0.1	1
Yams	–	0.2	–	–	–	–	1
Onions	0.15	0.2	0.075	0.15	–	0.06	1
Garlic	0.15	0.2	0.075	0.15	–	0.15	1
Shallots	0.15	0.2	0.075	–	–	0.2	1
Vegetables, incl. pulses	1	1	–	–	–	–	1
Pulses	1	–	–	–	1	–	1
Fruit (incl. fungi, tomato, rhubarb)	2	2	–	–	–	–	1
Strawberries	2	2	–	–	–	–	1
Dried vegetables and fruits	1	1	1	–	1	–	–
Cereals	1	1	–	–	–	–	–
Dried fruits	–	1	–	–	–	–	–
Flakes and germs of cereals for milk products	10	10	10	–	–	–	–
Flakes from cereals	–	1	–	–	1	–	–
Rice flour	4	4	4	–	–	–	–
Gum arabic	3	3	3	–	3	–	–
Seeds for sprouting	–	–	–	–	–	–	8

Adapted from the Official Journal of the European Union (2009) and FDA (2005)

BE Belgium, CZ Czech Republic, FR France, IT Italy, NL Netherlands, PL Poland, US United States

acceptability of the nuclear industry (Kilcast 1994). Acceptability in some countries has been almost impossible judging by people's belief or ignorance of nuclear industry coupled with statements by media reports and pressure groups all of which had an inordinate influence on public opinion.

Food irradiation regardless of critics is amongst the most meticulously investigated food preservation techniques over the past five decades and is still on-going (Kilcast 1994; Lee 2004). Whilst there is evidence showing public acceptance of the technology and debunking the belief that irradiation

Table 7 Sample of foods and ingredients of animal origin permitted for irradiation in the EU and US with doses

Products	Permitted dose (kGy)					
	BE	CZ	FR	IT	NL	US
Chicken meat	–	7	–	–	7	4.5–7
Poultry	5	5	5	–	–	4.5–7
Poultry (domestic fowls, geese, quails, ducks, guinea fowls, turkeys and pigeons)	7	7	–	–	–	4.5–7
Mechanically recovered poultry meat	5	5	5	–	–	4.5–7
Offal of poultry	5	5	5	–	–	–
Fresh, non-heated processed pork	–	–	–	–	–	0.3–1
Frozen frog legs	5	5	5	–	5	–
Dehydrated blood, plasma, coagulates	10	10	10	–	–	–
Fish and shellfish (incl. molluscs, eels, crustaceans)	3	3	–	–	–	5.5
Frozen peeled or decapitated shrimps	5	5	5	–	–	–
Shrimps	–	–	–	–	3	–
Egg white	5	3	3	–	3	3
Casein, caseinates	5	6	6	–	–	–

Adapted from the Official Journal of the European Union (2009) and FDA (2005)

BE Belgium, CZ Czech Republic, FR France, IT Italy, NL Netherlands, US United States

makes food radioactive, of reasonable concerns are the myths associated with the lack of good manufacturing practice, extreme nutrient loss and formation of toxic chemicals. The public worries that food with high microbial contamination will be deceptively sterilised with irradiation. The fear and belief of the public must be recognised by the companies, who in turn are obligatory to follow good manufacturing practice measures, to help alleviate the fear of the public which whilst not logical are not expected to disappear overnight. Development and introduction of adequate detection methods should also help reassure the public that the process is safe and not being misused (Kilcast 1994).

Implications for Food Irradiation

The need for elimination of chemical preservatives such as ethylene oxide for decontamination of herbs and spices necessitates the need and adoption of an alternative measure such as food irradiation since herbs and spices are not usually perceived by the public as a high-risk food ingredient. Irradiation of spices introduces no nutritional concerns since the ingredients are not known to add substantial amounts of vitamins to the diet. Irradiation as with other techniques is not the answer to poor manufacturing practices and as such can neither ‘clean up’ massive contamination in food nor make bad food better (Pryke and Taylor 1995). According to ACINF (1986), irradiation is unlikely to present any microbiological hazards provided emphasis was placed on good manufacturing practices especially in the toxin-producing bacteria whose toxin might not be eliminated by irradiation. Pre- and post-irradiation microbiological standards are a requirement for issuing licence for food irradiation (Pryke and Taylor 1995).

Although seven categories of foods are permitted for irradiation in the UK, there is a high degree of uncertainty in their adoptability. Irradiation of poultry at a dose not affecting the organoleptic quality would be an efficient way of decreasing the risk of *Salmonella* contamination. It will be interesting and important for poultry to be second category of food to be irradiated in the UK since *Salmonella* though significantly reduced might not be completely eliminated and the same applies for *Campylobacter*. Whilst some loss of some vitamins might occur, the loss would be equivalent to those observed in other preservative techniques and result in no nutritional deficiency. There are slight variations in the vitamin C content of irradiated fruits and vegetables, but at low permitted doses, these will be negligible in comparison to the natural variation in vitamin C content. Grain irradiation in the UK is unlikely to be of importance since it is not a major part of a diet (Kilcast 1994).

The arguments above are centred around the UK; these would however be different in reference to the context of another western country's diet, the main reason being the

availability of varied nutrients' distribution in the western diet from the low level of dependence on any particular food class. However, there might be a need for the monitoring of nutritional intake on a small segment of the population with dependence on a smaller range of food if the food were irradiated. It was based on this assumption that the ACINF proposed that although nutritional deficiencies from irradiation were insignificant in the diet, monitoring of the effect of irradiation on nutrient intake should be carried out (Kilcast 1994).

The joint FAO/IAEA/WHO Expert Committee (1981) acknowledged that irradiation does not result in any nutritional problem whilst looking at the implications for irradiation outside western countries. The use of irradiated foods by hospitals in England with limitations on low fat foods was reported by Harrison (1962), and these limitations might have contributed to the decline in their use due to lack of food varieties (Pryke and Taylor 1995).

The Value of Food Irradiation Worldwide

The viable benefit of radiation processing over other sterilisation methods to the public health facilitates endorsement by several national and international organisations food and health bodies alongside professional groups such as WHO, IAEA, FAO, American Dietetic Association and the Institute of Food Technologist (USEPA 2014; Huo et al. 2013). As documented by Skala et al. (1987) and Diehl et al. (1991), the key advantage of irradiation over other techniques is the minute alterations in the flavour, texture and nutritional quality. A study by Stevenson et al. (1995) reported no change in the sensory attributes between a chilled irradiated and non-irradiated beef and vegetable meal at a dose of 2 kGy. Food irradiation is being developed especially by the developing countries to minimise post-harvest losses which is the major cause of food shortage (Lee 2004). Uses include grain disinfection, reduction of spoilage of tropical fruits and elimination of fruit flies. It is used as sprouting inhibition in South American countries and East European countries to minimise losses of tuber crops such as onions, garlic and potatoes. Food irradiation is used mainly in developed countries for the reduction of pathogenic microorganisms in foods such as meat, chicken, frog legs and prawns. In 2012, *Campylobacter*, *Salmonella*, bacterial toxins and viruses were the major causes of the reported 5363 foodborne outbreaks in the European Union resulting in 55,453 human cases, 5118 hospitalisations and 41 deaths (EFSA and ECDC 2014).

Irradiation has proven to be a viable tool in the decontamination of spices when the observed microbial levels of imported spices are above limit and are often associated with food poisoning outbreaks (Farkas 1998; Farkas et al. 2014). Ethylene oxide was formerly used in the decontamination of spices, but due to the issue of chemical residue, it was banned

by several countries including the UK on safety grounds. Companies then reverted to using heat treatment which is often associated with loss of important volatiles which does not occur in irradiation. In 2012, the European Commission reported a total of 7972 tonnes of food consisting mainly of frog legs (36 %), poultry (35 %) and dried herbs and spices (15 %) irradiated in the European Union. Belgium, the Netherlands and France, the leading practising countries, accounted for a total of 64.7, 18.8 and 7.7 %, respectively, between them. Public perception and the fear of the nuclear industry, however, are making the application and adoption of irradiation difficult.

Allergenicity

During infancy and early childhood, cow's milk allergy is the most attributed form of food allergy (Docena et al. 1996). Several allergens are found in cow's milk, amongst which β -lactoglobulin, due to its absence in human milk, is classified as being most important (Savilahti and Kuitunen 1992). The approach of enzymatic hydrolysis with various proteolytic enzymes for reduction of milk allergenicity was reported by Taylor (1980), Asselin et al. (1989) and Schmidl et al. (1994). This method, however, has a shortfall of unacceptable taste produced by the existence of amino acids and bitter peptides (Lee et al. 2001). In vitro studies on sera have shown the ability of irradiation in reducing allergenic properties of some food samples (Hates et al. 1995; Lee et al. 2002a, b).

The maintenance of immune-modulatory properties of fermented milk products despite the lactic acid bacteria biologically inactivated may be one of the encouraging ways of applying food irradiation technology as adding value over microbiologically safer foods (Ham et al. 2009). The observed alteration in the binding ability of immunoglobulin E (IgE) against allergens reported by Hates et al. (1995) resulted from the structural denaturation which is a post-irradiation effect of proteins. A study by Ham et al. (2009) on the binding ability of rabbit antiserum to milk proteins in irradiated plain yoghurt showed that at 10-kGy dose the binding ability of irradiated plain yoghurt is significantly higher than the control or up to a 5-kGy dose using a rabbit serum. The IgE ELISA inhibition test by Lee et al. (2002a, b) also showed significant reduction in the IgE-binding capacities of irradiated ovalbumin and ovomucoid. Studies by Lee et al. (2001) on milk proteins at doses up to 10 kGy showed that the two proteins tested both experience structural change with different allergenicity and antigenicity and that the aggregation of the molecule might mask the epitopes of the proteins. The structural alteration of the epitopes of milk proteins by irradiation was supported (Ham et al. 2009). Success in the reduction of food allergens by irradiation was also reported by Lee et al. (2001), Byun

et al. (2002) and Jeon et al. (2002), where patients' immunoglobulin (IgE) depending on the applied dose was reported as not responding to the irradiated allergens. These outcomes showed that epitopes on the allergens were structurally changed by radiation treatment and that the irradiation technology can be applied to diminish allergenicity of allergic foods products (Byun et al. 2002).

Neutropenic Diets

Food products that are microbiologically stable and considered safe for consumption might not be the same for immunocompromised patients who generally required sterile food due to their state of health. Recommendation of irradiation for the preservation of foods for immunocompromised patients requiring sterile diet and the advantage in the availability of wide range of food choices was reported by Pryke and Taylor (1995). Foods regarded as high risk for this group of people include but not limited to meat, dairy products, eggs and seafood (especially shellfish). Doses between two and three times the recommended 10 kGy will guarantee whole sterility but will sequentially induce organoleptic disapproval as with other preservation techniques, hence the limitation of neutropenic diet for immunocompromised patients to low fat foods (Harrison 1962) to prevent rancidity and off-flavour resulting from high doses. Foods with sulphur-containing amino acid especially dairy products were documented to be unsuitable with the production of off-flavour after irradiation (Kilcast 1995). These, however, with the advancement in technology have been proven possible with treatment at lower doses such as in cheese (Abd El Baky et al. 1986; Bougle and Stahl 1994; Huo et al. 2013), ice cream (Hashishaka et al. 1990a; Kamat et al. 2000) and pasteurised milk (Sadoun et al. 1991). Production of a sterile diet, however, comes with an economic cost constraint since not a large proportion of the masses require it (Pryke and Taylor 1995). The use of a sterile diet for an immunocompromised patient at Hammersmith Hospital in London was documented until the early 1980s, whilst the last reported use at an English hospital was at the Charing Cross Children's Hospital until its closure in 1993 as reported by Pryke and Taylor (1995). Contrary to the rest of the UK, some hospitals in Scotland still make use of irradiated foods such as tea and coffee, fruit juices, ice creams (mostly for children), bread and breakfast cereal with exclusion on ready meals, meat and vegetables carried out on demand at Scottish Universities Research and Reactor Centre in East Kilbride at doses of at least 25 kGy (Pryke and Taylor 1995).

Conclusion

Radiation processing amongst other food processing techniques is the most thoroughly researched. Extensive research

has shown the effectiveness of radiation as a food processing technique in controlling food losses resulting from insect infestation and microorganisms. These lead to endorsing bodies concluding that food irradiated to any dose suitable to attain the anticipated technological objectives is both safe to consume and nutritionally adequate and is also deemed wholesome throughout the technological useful dose range from below 10 kGy to intended doses above 10 kGy. Also, application of doses above 10 kGy can be regarded as chemically safe and nutritionally stable for neutropenic diets. Nevertheless, less attention was given to dairy products (milk, yoghurt, cheese and ice cream) due to the potential adverse effect on organoleptic qualities in high fat content products. Radiation is like every other food preservative techniques when abuse and misuse can affect the nutritional quality and chemical composition if applied in doses above those necessary. After long and exhaustive studies on food irradiation, it was proven that irradiated foods are wholesome and nutritious and thus endorsed by several health organisations and given legal clearance for human consumption by the governments of many countries. Approved in over 50 countries, food irradiation is proven to be safe and has the potential for use in preservation and extending the shelf life of certain dairy products. However, its full acceptance and incorporation by the food industries is slow and often controversial. These challenges of market penetration arose from consumers' scepticism despite being worldly commercialised and safety evidence documented from decades of research. For successful adaptation, more studies need to be done on the consumer attitudes whilst not overlooking the standardisation of process parameters and techno-economic feasibility of scaling up such facilities. The need for consumer education on the principles and immense benefits of food irradiation is imperative. It has the potential for use in preservation and extending the shelf life of certain milk and milk products.

Acknowledgments The authors wish to acknowledge the great support received from all the team at Synergy Health Swindon in the UK, now part of STERIS for giving us access and for allowing us to conduct the experiments during a busy time schedule.

References

- Abd El Baky, A. A., Farahat, S. M., Rabie, A. M., & Mobasher, S. A. (1986). The manufacture of Ras cheese from gamma irradiated milk. *Food Chemistry*, 20, 201–212.
- ACINF. (1986). *The safety and wholesomeness of irradiated foods*. London: Advisory Committee on Irradiated and Novel Foods, HMSO.
- Adeil Pietranera, M. S., Narvais, P., Horak, C., & Kairiyama, E. (2003). Irradiated ice creams for immunosuppressed patients. *Radiation Physics and Chemistry*, 66, 357–365.
- Allothman, M., Rajeev, B., & Karim, A. A. (2009). Effects of radiation processing on phytochemicals and antioxidants in plant produce. *Trends in Food Science and Technology*, 20, 201–212.
- Aquino, K. A.S. (2012). Sterilization by gamma irradiation, gamma radiation. In Adrovic, F. (Ed.), *Gamma radiation* (pp 171–206).
- Arvanitoyannis, I. S., & Tserkezou, P. (2010). *Application of irradiation on milk and dairy products. Irradiation of food commodities: techniques, applications, detection, legislation, safety and consumer opinion*. London: Elsevier.
- Arvanitoyannis, I. S., Stratakos, A., & Mente, E. (2009). Impacts of irradiation on fish and seafood shelf life: a comprehensive review of applications and irradiation detection. *Critical Reviews in Food Science and Nutrition*, 49, 68–112.
- Asselin, J., Hebert, J., & Amiot, J. (1989). Effects of in-vitro proteolysis on the allergenicity of major whey proteins. *Journal of Food Science*, 54(4), 1037–1039.
- Bandekar, J., Kamat, A., & Thomas, P. (1998). Microbiological quality of the dairy product pedha and its improvement using gamma irradiation. *Journal of Food Safety*, 18(3), 221–230.
- Barbano, D. M., MA, Y., & Santos, M. V. (2006). Influence of raw milk quality on fluid milk shelf life. *Journal of Dairy Science*, 89(E. suppl), E15–E19.
- Barros-Velazquez, J. (2011). Innovations in food technology special issue. *Food and Bioprocess Technology*, 4(6), 831–832.
- Berejka, A. J., & Larsen, S. (2014). Enhanced wood durability from radiation-cured penetrants. *Radiation Technology Report*, 2, 15–21.
- Berrocal, D., Arias, M. L., Henderson, M., & Wong, E. (2002). Evaluation of the effect of probiotic cultures over *Listeria monocytogenes* during the production and storage of yogurt. *Archivos Latinoamericanos de Nutrición*, 52(4), 375–380.
- Blank, G., Shamsuzzaman, K., & Sohal, S. (1992). Use of electron-beam irradiation for mold decontamination on cheddar cheese. *Journal of Dairy Science*, 75(1), 13–18.
- Bougle, D. L., & Stahl, V. (1994). Survival of *Listeria monocytogenes* after irradiation treatment of camembert cheeses made from raw milk. *Journal of Food Protection*, 57(9), 811–813.
- Brault, D., D'Aprano, G., & Lacroix, M. (1997). Formation of free-standing sterilized edible films from irradiated caseinates. *Journal of Agricultural and Food Chemistry*, 45, 2964–2969.
- Brewer, M. S. (2009). Irradiation effects on meat flavour: a review. *Meat Science*, 81, 1–14.
- Buchin, S., Delague, V., Duboz, G., Berdague, J. L., Beuvier, E., Pochet, S., & Grappin, R. (1998). Influence of pasteurization and fat composition of milk on the volatile compounds and flavor characteristics of a semi-hard cheese. *Journal of Dairy Science*, 81(12), 3097–3108.
- Byun, M. W., Lee, J. W., Yook, H. S., Jo, C. R., & Kim, H. Y. (2002). Application of gamma irradiation for inhibition of food allergy. *Radiation Physics and Chemistry*, 63(3–6), 369–370.
- Camillo, A., & Sabato, S. F. (2004). Effect of combined treatments on viscosity of whey dispersions. *Radiation Physics and Chemistry*, 71(1), 105–108.
- Cathalin, J., & McNulty, P. (1996). Textural gain and subsequent loss in irradiated apples, carrots and potatoes with increase in dose from 0.03 to 1.0 kGy. *Journal of Food Processing and Preservation*, 20, 403–415.
- Chen, H. (1995). Functional properties and application of edible films made of milk proteins. *Journal of Dairy Science*, 78, 2563–2583.
- Cieřla, K., Salmieri, S., Lacroix, M., & Le Tien, C. (2004). Gamma irradiation influence on physical properties of milk proteins. *Radiation Physics and Chemistry*, 71, 93–97.
- Cousin, M. A. (1982). Presence and activity of psychrotrophic microorganisms in milk and dairy products: a review. *Journal of Food Protection*, 45, 172–207.
- Crawford, L. M., & Ruff, E. H. (1996). A review of the safety of cold pasteurization through irradiation. *Food Control*, 7(2), 87–97.

- Delincee, H., & Ehlermann, D. A. E. (1989). Recent advances in the identification of irradiated food. *International Journal of Radiation Applications and Instrumentation. Part C. Radiation Physics and Chemistry*, 34(6), 877–890.
- Diehl, J. F. (1985). The role of WHO in the field of food irradiation. *Radiation Physics and Chemistry*, 25(1–3), 73–74.
- Diehl, J. F. (2002). Food irradiation—past, present and future. *Radiation Physics and Chemistry*, 63, 211–215.
- Diehl, J. F., Hasselmann, C., & Kilcast, D. (1991). Regulation of food irradiation in the European community: is nutrition an issue? *Food Control*, 2, 212–219.
- Dionísio, A. P., Gomes, R. T., & Oetterer, M. (2009). Ionizing radiation effects on food vitamins—a review. *Brazilian Archives of Biology and Technology*, 52(5), 1267–1278.
- Docena, G. H., Fernandez, R., Chirido, F. G., & Fossati, C. A. (1996). Identification of casein as the major allergenic and antigenic protein of cow's milk. *Allergy*, 51(6), 412–416.
- Dong, F. M., Lee, C. J., Rasco, B. A., & Hungate, F. P. (1989). Effects of gamma-irradiation on the contents of thiamin, riboflavin, and vitamin-B₁₂ in dairy-products for low microbial diets. *Journal of Food Processing and Preservation*, 13(3), 233–244.
- EFSA. (2011). Statement summarising the conclusion and recommendations from the opinions on the safety of irradiation of food by the BIOHAZ and CEF panels. *EFSA Journal*, 9(4), 2107. 1–155.
- EFSA & ECDC. (2014). The European Union summary report on trends and sources of zoonoses, zoonotic agents and food-borne outbreaks in 2012. *EFSA Journal*, 12(2), 3547. 312 pp.
- Ehlerman, D. A. E. (2014). Safety of food and beverages: safety of irradiated foods. In M. Yasmine (Ed.), *Encyclopedia of food safety* (Vol. 3, pp. 447–452). Waltham: Academic.
- Elias, P. S., & Cohen, A. J. (1977). Radiation chemistry of major food components. Its relevance to the assessment of the wholesomeness of irradiated foods. Elsevier.
- Ennahar, S., Kuntz, F., Strasser, A., Bergaentzle, M., Hasselmann, C., & Stahl, V. (1994). Elimination of *Listeria monocytogenes* in soft and red smear cheese by irradiation with low energy electrons. *International Journal of Food Science and Technology*, 29(4), 395–403.
- Fan, X., & Sommers, C. H. (Eds.). (2013). *Food irradiation research and technology* (2nd ed.). Ames: Wiley-Blackwell.
- Farag, K. W., Lyng, J. G., Morgan, D. J., & Cronin, D. A. (2008). A comparison of conventionally and radio frequency tempering of beef meats: effects on product temperature distribution. *Meat Science*, 80(2), 488–495.
- Farag, K. W., Lyng, J. G., Morgan, D. J., & Cronin, D. A. (2011). A comparison of conventionally and radio frequency thawing of beef meats: effects on product temperature distribution. *Food and Bioprocess Technology*, 4(7), 1128–1136.
- Farber, J. M., & Peterkin, P. I. (1991). *Listeria monocytogenes*, a food-borne pathogen. *Microbiological Reviews*, 55(3), 476–511.
- Farkas, J. (1998). Irradiation as a method for decontaminating food: a review. *International Journal of Food Microbiology*, 44, 189–204.
- Farkas, J., & Mohacsi-Farkas, C. (2011). History and future of food irradiation. *Trends in Food Science and Technology*, 22, 121–126.
- Farkas, J., Ehlermann, D. A. E., & Mohácsi-Farkas, C. (2014). Food technologies: food irradiation. In M. Yasmine (Ed.), *Encyclopedia of food safety* (Vol. 3, pp. 178–186). Waltham: Academic.
- FDA (2005). Irradiation in the production, processing, and handling of food. Federal Register. Final Rule. August 16, 2005, 70(157), 48057–48073.
- Ford, J. E., Gregory, M. E., & Thompson, S. Y. (1962). The effect of gamma irradiation on the vitamins and proteins of liquid milk. *International Dairy Congress. Abstrac.*, 917, 917–923.
- Gekko, K., & Timasheff, S. (1981). Mechanism of protein stabilization by glycerol: preferential hydration in glycerol-water mixtures. *Biochemistry*, 20, 4667–4676.
- Grandison, A. S. (2012). Irradiation. Food processing handbook, second edition, 153–177.
- Guilbert, S., Gontard, N., & Gorris, L. G. M. (1996). Prolongation of the shelf-life of perishable food products using biodegradable films and coatings. *LWT—Food Science and Technology*, 29(1), 10–17.
- Hallman, G. J. (2011). Phytosanitary applications of irradiation. *Comprehensive Reviews in Food Science and Food Safety*, 10, 143–151.
- Ham, J. S., Jeong, S. G., Lee, S. G., Han, G. S., Jang, A., Yoo, Y. M., Chae, H. S., Kim, D. H., Kim, H. J., Lee, W. K., & Jo, C. (2009). Quality of irradiated plain yogurt during storage at different temperatures. *Asian-Australasian Journal of Animal Sciences*, 22(2), 289–295.
- Harrison, R. (1962). A method of preparing service of sterilized meals. *Nutrition*, 16, 105–111.
- Hashisaka, A. E., Weagant, S. D., & Dong, F. M. (1989). Survival of *Listeria-monocytogenes* in mozzarella cheese and ice-cream exposed to gamma irradiation. *Journal of Food Protection*, 52(7), 490–492.
- Hashisaka, A. E., Einstein, M. A., Rasco, B. A., Hungate, F. P., & Dong, F. M. (1990a). Sensory analysis of dairy products irradiated with Cobalt 60 at –78°C. *Journal of Food Science*, 55(2), 404–408.
- Hashisaka, A. E., Matches, J. R., Batters, Y., Hungate, F. P., & Dong, F. M. (1990b). Effects of gamma irradiation at –78°C on microbial populations in dairy products. *Journal of Food Science*, 55(5), 1284–1289.
- Hates, D. J., Murano, E. A., Murano, P. S., Olson, D. G., & Sapp, S. G. (1995). *Food irradiation* (pp. 71–73). Ames: Iowa State University Press.
- Huo, J. X., Bai, C. Y., Guo, L. H., & Zhao, Z. (2013). Effect of electron beam irradiation on the shelf life of mozzarella cheese. *International Journal of Dairy Technology*, 66(3), 352–358.
- IAEA. (2012). Irradiated food authorization database. Available from: <http://nucleus.iaea.org/ifa/FoodAuthorisationDisplay.aspx>. Accessed 05 Sep 2014.
- International Consultative Group on Food Irradiation (ICGFI). (1999). *In facts about food irradiation*. United Kingdom: Buckinghamshire. http://moreira.tamu.edu/BAEN625/TOC_files/foodirradiation.pdf.
- JECFI (1981). Wholesomeness of irradiated food. WHO technical report, Series 659, Geneva, Switzerland.
- Jeon, G. R., Lee, J. W., Byun, M. W., & Lee, S. Y. (2002). Reduced allergenicities of irradiated egg white ovalbumin determined by skin prick test and ELISA inhibition test. *Journal of Asthma, Allergy and Clinical Immunology*, 22, 711–719.
- Kaferstein, F. K. (1990). Food irradiation and its role in improving the safety and security of food. *Food Control*, 1, 211–214.
- Kamat, A., Warke, R., Kamat, M., & Thomas, P. (2000). Low-dose irradiation as a measure to improve microbial quality of ice cream. *International Journal of Food Microbiology*, 62(1–2), 27–35.
- Khwaldia, K., Perez, C., Banon, S., Desobry, S., & Hardy, J. (2004). Milk proteins for edible films and coatings. *Critical Reviews in Food Science and Nutrition*, 44(4), 239–251.
- Kilcast, D. (1994). Effect of irradiation on vitamins. *Food Chemistry*, 49(2), 157–164.
- Kilcast, D. (1995). Food irradiation: current problems and future potential. *International Biodeterioration and Biodegradation*, 36(3–4), 279–296.
- Kim, H. J., Jo, C., Lee, N. Y., Ham, J. S., Lee, W. K., & Byun, M. W. (2005). *Irradiation of food-borne pathogens inoculated into chocolate ice cream*. International symposium “New Frontier of Irradiated Food and Non-Food Products”. Bangkok: KMUTT.
- Knorr, D. (1999). Novel approaches in food-processing technology: new technologies for preserving foods and modifying function. *Current Opinion in Biotechnology*, 10(5), 485–491.

- Knorr, D., Froehling, A., Jaeger, H., Reineke, K., Schlueter, O., & Schoessler, K. (2011). Emerging technologies in food processing. *Annual Review of Food Science and Technology*, 2, 203–235.
- Kume, T., & Todoriki, S. (2013). Food irradiation in Asia, the European Union and the United States: a status update. *Radioisotopes*, 62(5), 291–299.
- Kume, T., Furuta, M., Todoriki, S., Uenoyama, N., & Kobayashi, Y. (2009). Status of food irradiation in the world. *Radiation Physics and Chemistry*, 78(3), 222–226.
- Lacroix, M., Le, T. C., Quattria, B., Yu, H., Letendre, M., Sabato, S. F., Mateescu, M. A., & Patterson, G. (2002). Use of gamma irradiation to produce films from whey, casein and soya proteins: structure and functional characteristics. *Radiation Physics and Chemistry*, 63, 827–832.
- Le Tien, C. L., Vachon, C., Mateescu, M. A., & Lacroix, M. (2001). Milk protein coatings prevent oxidative browning of apples and potatoes. *Journal of Food Science*, 66, 512–516.
- Lee, S. (2004). Irradiation as a method for decontaminating food. *Internet Journal of Food Safety*, 3, 32–35.
- Lee, J. W., Kim, J. H., Yook, H. S., Kang, K. O., Lee, S. Y., Hwang, H. J., & Byun, M. W. (2001). Effects of gamma radiation on the allergenic and antigenic properties of milk proteins. *Journal of Food Protection*, 64(2), 272–276.
- Lee, J. W., Lee, K. Y., Lee, S. Y., Jo, C., Yook, H. S., Kim, H. Y., & Byun, M. W. (2002a). Allergenicity of hen's egg ovomucoid gamma irradiated and heated under different pH condition. *Journal of Food Protection*, 65, 1196–1199.
- Lee, S. Y., Trezza, T. A., Guinard, J. X., & Krochta, J. M. (2002b). Whey protein-coated peanuts assessed by sensory evaluation and static headspace gas chromatography. *Journal of Food Science*, 67, 1212–1218.
- Mahapatra, A. K., Muthukumarappan, K., & Julson, J. L. (2005). Applications of ozone, bacteriocins and irradiation in food processing: a review. *Critical Reviews in Food Science and Nutrition*, 45(6), 447–462.
- Matloubi, H., Aflaki, F., & Hadjiezadegan, M. (2004). Effect of γ -irradiation on amino acids content of baby food proteins. *Journal of Food Composition and Analysis*, 17(2), 133–139.
- McNulty, P. (1988). Food and health—modern techniques used in the production, preparation and presentation of food which may have a detrimental effect on human health. Paper presented at the December 8th, 1988 meeting of the Midland Regional Clinical Veterinary Society in the Bloomfield House Hotel, Mullingar.
- Mezgheni, E., D'Aprano, G., & Lacroix, M. (1998). Formation of sterilized edible films based on caseinates: effects of calcium and plasticizers. *Journal of Agriculture and Food Chemistry*, 46, 318–324.
- Molins, R. A. (Ed.). (2001). *Food irradiation: principles and applications* (p. 488). New York: Wiley.
- Norton, T., & Sun, D. W. (2008). Recent advances in the use of high pressure as an effective processing technique in the food industry. *Food and Bioprocess Technology*, 1, 2–34.
- O'Bryan, C. A., Crandall, P. G., Ricke, S. C., & Olson, D. G. (2008). Impact of irradiation on the safety and quality of poultry and meat products: a review. *Critical Reviews in Food Science and Nutrition*, 48, 442–457.
- Official Journal of the European Union. (2009). List of member states' authorisations of food and food ingredients which may be treated with ionizing radiation.
- Perko, B. (2011). Effects of prolonged storage on microbiological quality of raw milk. *Mljekarstvo*, 61(2), 114–124.
- Prejean, J. E. (2001). *Food irradiation: why aren't we using it?* Report of LEDA at Harvard Law School, available at: <http://leda.law.harvard.edu/leda/data/403/Prejanpap.html>.
- Pryke, D. C., & Taylor, R. R. (1995). The use of irradiated food for immunosuppressed hospital patients in the United Kingdom. *Journal of Human Nutrition and Dietetics*, 8, 411–416.
- Roberts, P. B. (2014). Food irradiation is safe: half a century of studies. *Radiation Physics and Chemistry*, 105, 78–82.
- Sabato, S. F., & Lacroix, M. (2002). Radiation effects on viscosimetry of protein based solutions. *Radiation Physics and Chemistry*, 63, 357–359.
- Sadoun, D., Couvercelle, C., Strasser, A., Egler, A., & Hasselmann, C. (1991). Low dose irradiation of liquid milk. *Michwissenschaft*, 46, 295–299.
- Savilahti, E., & Kuitunen, M. (1992). Allergenicity of cow milk-proteins. *Journal of Paediatrics*, 121(5), S12–S20.
- SCF (Scientific Committee on Food). (1992). Food science and techniques. Reports of the Scientific Committee for Food (thirty-second series). Available at: http://aei.pitt.edu/40841/1/32nd_food.pdf
- SCF (Scientific Committee on Food). (2002). Statement of the Scientific Committee on Food on a Report on 2-alkylcyclobutanones. Available at: http://ec.europa.eu/food/fs/sc/scf/out135_en.pdf
- Schmidl, M. K., Taylor, S. L., & Nordlee, J. A. (1994). Use of hydrolysate based products in special medical diets. *Food Technology*, 48(10), 77–85.
- Seisa, D., Osthoff, G., Hugo, C., Hugo, A., Bothma, C., & Van der Merwe, J. (2004). The effect of low-dose gamma irradiation and temperature on the microbiological and chemical changes during ripening of cheddar cheese. *Radiation Physics and Chemistry*, 69(5), 419–431.
- Skala, J. H., McGown, E. L., & Waring, P. P. (1987). Wholesomeness of irradiated foods. *Journal of Food Protection*, 50, 150–160.
- Song, H. P., Byun, M. W., Jo, C., Lee, C. H., Kim, K. S., & Kim, D. H. (2007). Effects of gamma irradiation on the microbiological, nutritional and sensory properties of fresh vegetable juice. *Food Control*, 18, 5–10.
- Steele, J. H. (2001). Food irradiation: a public health challenge for the 21st century. *Journal of Food Safety*, 33, 376–377.
- Stevenson, M. H., Stewart, E. M., & McAteer, N. J. (1995). A consumer trial to assess the acceptability of an irradiated chilled ready meal. *Radiation Physics and Chemistry*, 46, 785–788.
- Taylor, S. (1980). Food allergy: the enigma and some potential solutions. *Journal of Food Protection*, 43, 300–306.
- Temur, C., & Tiryaki, O. (2013). Irradiation alone or combined with other alternative treatments to control postharvest diseases. *African Journal of Agricultural Research*, 8(5), 421–434.
- Teuber, M. (2000). Fermented milk products. In *The microbiological safety and quality of food* (Vol. 1, pp. 535–585). Gaithersburg: Aspen.
- Tsiotsias, A., Savvaidis, I., Vassila, A., Kontominas, M., & Kotzekidou, R. (2002). Control of *Listeria monocytogenes* by low-dose irradiation in combination with refrigeration in the soft whey cheese 'Anthotyros'. *Food Microbiology*, 19(2–3), 117–126.
- USEPA, US Environmental Protection Agency (2014). Food irradiation: food labeling. (http://www.epa.gov/radiation/sources/food_labeling.html). Accessed 03 July 2014.
- USFDA. (2008). U.S. Food and Drug Administration. Irradiation: a safe measure for safer iceberg lettuce and spinach. Available from: <http://www.fda.gov/ForConsumers/ConsumerUpdates/ucm093651.htm>.
- Vachon, C., Yu, H. L., Yesah, R., Alain, R., St-Gelais, D., & Lacroix, M. (2000). Mechanical and structural properties of milk protein edible films cross-linked by heating and gamma irradiation. *Journal of Agricultural and Food Chemistry*, 48, 3202–3209.
- Varga, L. (2006). Effect of acacia (*Robinia pseudo-acacia* L.) honey on the characteristic microflora of yogurt during refrigerated storage. *International Journal of Food Microbiology*, 108(2), 272–275.
- Walker, S. J., Archer, P., & Banks, J. G. (1990). Growth of *Listeria monocytogenes* at refrigeration temperatures. *Journal of Applied Bacteriology*, 68(2), 157–162.
- World Health Organization. (1994). *Safety and nutritional adequacy of irradiated food*. Geneva: World Health Organization.

- World Health Organization. (1999). High-dose irradiation: wholesomeness of food irradiated with doses above 10 kGy. Report of a Joint FAO/IAEA/WHO Expert Committee. Technical Report Series No. 890: i–iv, 1–197.
- Yagoub, S. O., Awadalla, N. E., & El Zubeir, I. E. M. (2005). Incidence of some potential pathogens in raw milk in Khartoun North Sudan and their susceptibility to antimicrobial agents. *International Journal of Animal and Veterinary Advances*, 4, 341–344.
- Ziporin, Z. Z., Kraybill, H. F., & Thach, H. J. (1957). Vitamin content of foods exposed to ionizing radiations. *The Journal of Nutrition*, 63(2), 201–209.