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Employing Ionizing Radiation to Enhance Food Safety – a Review

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Abstract

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Food irradiation has been employed to ensure food safety or food sterility, extend its shelf-life and reduce the losses due to sprouting and ripening or pests. In the Czech Republic, mainly spices, mixed spices and dried vegetable are exposed to ionizing radiation. The greatest suppliers of irradiated foodstuffs in Europe are Belgium, France and the Netherlands. In the USA, food irradiation is more common and there are also attempts to enforce irradiation not only for food safety, but also for technological purposes. Even though irradiation is a prospective technology, its application causes physical-chemical and biochemical changes that may affect nutritional adequacy and sensory characteristics of irradiated food. In this paper, the chemical changes of basic food components (proteins, saccharides, fats) are reviewed. The chemical changes result in radiolytic products whose risks are still subject of scientific research. It is expected that the main use of gamma irradiation will be treatment of diets for patients suffering from different disorders of the immune system, allergic patients or for the army and space flights. In the production of raw or heat non-processed foodstuffs, irradiation may be a critical control point (CCP).

Gamma irradiation, food, legislative bases, radiation effects, nutritional adequacy

The Purpose of Food Irradiation

In recent decades, food irradiation has become one of the most discussed technologies for food safety and shelf-life.

The purpose of food irradiation is the same as for freezing, high-temperature treatment and chemical treatment, i.e. removal of micro-organisms causing food spoilage. The aim is to prolong the shelf-life of foods kept under various conditions such as in shops and households, and to eliminate pathogenic organisms that cause diseases as a result of food consumption. Radiation doses usually employed for food irradiation destroy the majority of micro-organisms but not all of them, i.e. the irradiated food is not sterilized. As with other foods, the customer must therefore use other methods to eliminate pathogenic micro-organisms and risks ensuing from their consumption (refrigeration, cooking, etc.). For example, current radiation doses do not destroy the bacteria that cause botulism (Brennand 1995). Radiation treatment at doses 2-7 kGy can effectively eliminate potentially pathogenic non-spore-forming bacteria including both long recognized pathogens such as *Salmonella* and *Staphylococcus aureus* as well as pathogens such as *Campylobacter, Listeria monocytogenes* or *Escherichia coli O157:H7*. Candidates for radiation decontamination are mainly poultry and red meat, egg products and fishery products (Farkas 1998). Irradiation is often called "cold pasteurization" because of its remarkable reduction of a number of dangerous microorganisms, and because of a negligible loss of nutrients and low degree of sensory changes (Wood and Bruhn 2000). The public often asks if irradiated food can be radioactive. This question can easily be clarified since radioactivity in food may arise in two ways: 1) by contamination of food in question by radionuclides and 2) by induced

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radioactivity during the interaction of high-energy radiation (mainly neutrons) with food nuclei. The process of irradiation includes food passage through the radiation field, however, food itself never makes contact with radioactive substances. The energy of ionizing radiation applied for food irradiation is not high enough to disintegrate the atomic nuclei in food (Brennand 1995).

Ionizing radiation is more and more frequently used for sterilization purposes. It can be used for sterilization of diets for laboratory animals, pathogen-free animals and/or animals used for the health control programmes. Feeding diets treated with ionizing radiation reduces the risk of contamination originating in animal herds (Holub and Baranyiová 1989). The sterilization procedure is assessed not only for its efficiency of the destruction of undesired micro-organisms, but also for its effect on nutrient quality, physical properties and the shelf-life of food to be treated. For the majority of these features, the traditional heat and chemical treatment procedures seem to be less advantageous compared to ionizing radiation. In addition to undesired effects on physical properties and food shelf-life, the traditional methods reduce the utilization of biological proteins and they cause a remarkable destruction of many important components of nutrients. For these reasons, sterilization by radiation is substantially more sensitive and constant. Foodstuffs sterilized by irradiation may be stored for many years without refrigeration similar to food sterilized by high temperatures.

Food irradiation may be also used to reduce losses caused by premature ripening of fruits, sprouting of vegetables and pests. In such cases, irradiation can replace the chemical treatment of foodstuffs (fruits, vegetables, spices and crops). The advantage of the process, compared to the above-mentioned chemical treatment is that no residues are formed in foodstuffs (Donahaye 2000).

Food Irradiation in the Czech Republic

Only a limited range of foods stipulated by the Regulation of Ministry of Health No. 297, 1997, may be treated by ionizing radiation in the Czech Republic. This Regulation defines the types, groups and subgroups of foods that may be treated by ionizing radiation for a specified purpose, and it also specifies the maximum permissible absorbed radiation doses. Other foods may be treated by ionizing radiation only if safety cannot be achieved by different methods, and if no health risk arises for the consumers, and food safety and quality are not deteriorated. In the Czech Republic, mainly spices such as pepper and ground pepper, mixed spices and dried vegetables are exposed to ionizing radiation. In the Czech Republic, foodstuffs may be irradiated by ^{60}Co and ^{137}Cs sources, X-rays with energy not exceeding 5 MeV and accelerated electrons with energy not exceeding 10 MeV. To inform the customers, irradiated foodstuffs must be indicated by both the label of "Irradiated by ionizing radiation" and by the respective graphic symbol. The following kinds of foods may be exposed to ionizing radiation in this country: onions and root vegetable, potatoes and potato products (the maximum permissible absorbed dose is 0.2 kGy), fresh fruits and vegetables (doses from 1.0 to 2.5 kGy), mill crop products, dry shell crops, oil seeds, legumes, dry vegetables and fruits (dose of 1.0 kGy), fish, sea animals, frozen frog's legs (doses from 2.0 to 5.0 kGy), meat, poultry (doses from 3.0 to 7.0 kGy), dry vegetables, spices, herb teas (doses from 1.0 to 10.0 kGy), dry fish, and dry meat (dose of 1.0 kGy).

Food Irradiation in the EU countries, the U.S.A., Australia and New Zealand

In the European Union, the opinions on use of irradiation differ in member countries, and the approach of the individual member states is based on their legislation in force. There have been many attempts to unify and harmonize the differences in legislation to be acceptable for the majority of countries (Neyssen 2000). In the United Kingdom, food irradiation was permitted in 1990. In principle, there is a wide range of foods to be irradiated for different purposes. However, food irradiation in practice has not been applied nearly as much, given by the permanent radiophobia of consumers related to the safety of irradiated foodstuffs (Woolston 2000). The greatest suppliers of irradiated foodstuffs are the following countries: Belgium, France and the Netherlands (up to 20,000 tons of food per year) (Brennand 1995). A negative attitude can be observed, in particular, among the German experts. The reason for this view is the knowledge about formation of 2-alkylcyclobutanones arising in the course of fat irradiation, and the fact that their toxicity has not yet been fully clarified.

In the USA, food irradiation is more common. The studies have even shown an increased customer readiness to buy irradiated foodstuffs that gives them a greater guarantee of food product safety (Hunter 2000). There is also an attempt to enforce irradiation not only for food safety, but also for technological purposes, for example, improving the colour of meat products (Byun et al. 1999). The Food and Drug Administration (FDA) controls food irradiation in the USA. Their regulations and directives stipulate the permitted sources, the maximum permissible doses, and the kinds of food which may be irradiated, along with the records that should be kept and the identification methods of food to be treated. The records containing all information on the treatment, types of material and the parameters of ionizing radiation doses should be filed for one year. The exact records are necessary for checks whether the regulations are observed, because with routine methods it is not possible to detect irradiated food and to determine the dose in retrospect. Irradiated food should be identified by both the graphic symbol and the label of “Treated by radiation” or “Irradiated by ionizing radiation”. The permitted radiation sources are as follows: gamma radiation, X-rays and electrons.

In Australia and New Zealand, the Ministry of Health controls food irradiation, and the so-called Food Standard was approved for this purpose. This Standard prohibits food and food product irradiation without a special permission that is issued by the Ministry of Health. The treatment of food by ionizing radiation is permitted only if this is a necessary technological requirement, or the radiation treatment will provide for food safety. By no means should food irradiation replace the proper production practice. This Standard also specifies the permitted radiation sources, food that may be irradiated, the requirements for filing the records, labelling the irradiated food, the minimum and maximum radiation doses and the conditions of irradiation. The permitted ionizing radiation sources are as follows: ^{60}Co sources, X-ray sources with energies not exceeding 5 MeV and electrons emitted from the sources with energies not exceeding 10 MeV. The records must be kept on premises where food is irradiated. Furthermore, the name and the quantity of irradiated foodstuffs, the minimum shelf-life, the type of irradiation process used, the minimum and maximum absorbed doses and the date of irradiation should be recorded. These records should be filed for the time that exceeds the minimum shelf-life of food irradiated by one year. The following information should be indicated on packages that food is irradiated: “Irradiated by ionizing radiation”, “Irradiated by ionizing electrons”, or „Irradiated + product name“.

Food irradiation has been approved in 37 countries for more than 40 food products. The official international certificates of WHO (World Health Organisation) and IAEA (International Atomic Energy Agency) have been provided for this treatment (Brennand 1995).

Changes in Food Treated by Ionizing Radiation

On one hand food irradiation is a prospective technology providing food shelf-life and food health safety but on the other hand it causes both physical-chemical changes (Dogbevi et al. 1999) and biological changes that may upset the nutritional value and the sensory properties of irradiated food (Giroux and Lacroix 1998). There is scientific evidence that changes caused by irradiation are fewer than those entailed by cooking. These changes are so evident that the consumer can recognize them easily compared to foodstuffs that are irradiated by usual low radiation doses which cannot be distinguished by sight, smell and taste from not irradiated food. Irradiated food can be identified retrospectively only by complex methods, for example, by electron resonance spectroscopy (Rachubik 2000). All well-known methods used during food production processes including food storage at room temperature may reduce the content of some nutrients. For low radiation doses (up to 10 kGy), the losses are either non-measurable or non-significant. For higher doses (above 10 kGy) that are used for the sterilization and the control of dangerous pathogens, the nutritive losses are evaluated as lower or comparable to those that arise during cooking and refrigerating (Brennand 1995). For example, meat colour is the most significant sensory and quality factor that is followed by a customer (Hood 1980; Dvořák et al. 2001). Luchsinger (1996) states that after exposure to 5 kGy no changes in meat colour were observed. Similarly, Nanke et al. (1999) describes that after exposure of meat to 5 kGy the particular colour indices have changed but the final meat colour was not affected. For the majority of foods, sensory and temperature changes are not remarkable for low doses, however, for higher doses, e.g. higher than 5 kGy, the temperature of irradiated food will increase, and the sensory changes will be also marked, for example, as foreign smell and getting brown (Ahn et al. 2000). Irradiation of meat causes distinct off-flavours, the intensity of which is dose- and temperature-dependent (Smulders et al. 1991). Furthermore, this technology cannot be applied to treat all kinds of food, for example, it will cause undesired taste changes in milk products and softening of the flesh of some fruits.

The chemical changes result in formation of radiolytic products. The effects of these products are continuously studied and have not yet been satisfactory solved so far. The opponents of irradiation often warn that the radiolytic products may be dangerous, but the protagonists of irradiation confirm the safety of irradiated food.

Post-radiation Protein Changes

The radiation-chemical changes in proteins depend on irradiation conditions. If proteins are irradiated in the solid state and in a clear chemical form, the absorption of radiation energy gives rise to free radicals. If proteins are irradiated in an aqueous solution or a mixture of other substances, the radiation-chemical changes of amino acids will appear due to water radicals and radicals that arise from the individual mixture components. After irradiation of sulphur containing amino acids e.g., methionine, cysteine and cystine, volatile products are formed e.g., mercaptan and sulfane. As a consequence of fast energy transfer, simultaneous deamination or decarboxylation of a terminal amino acid and a breakage of the peptidic chain can be observed in the peptidic chain of proteins. These reactions will result in both products with an amidic group and products of appropriate acid (no oxygen) or keto-compounds (oxygen is present). If proteins are irradiated in aqueous solutions, mainly the reactions of hydrated electrons and hydroxyl radicals may be observed. The peptide chain will break or radicals will migrate to the side chains of the amino-acids that are labile to radiation, for example, cysteine, cystine, methionine, tyrosine, phenylalanine, histidine, tryptophan and lysine. Radiation splitting of hydrogen and -S-S- bridges leads to development of protein molecules and loss of their organized structure. On one hand the original bond that stabilizes the secondary and tertiary structure can be destroyed by either the reduction of the -S-S- bond or the oxidation of the -SH group, and, on the other hand, new bonds may originate in the other places, which leads to a change in protein configuration. The intermolecular -S-S- bonds that contribute to radiation aggregation are also formed, in particular, during irradiation of globular proteins. However, the above-described changes are related to pure chemical substances whereas food proteins are built in complex mixtures that contain the different substances in which the individual components protect each other against the effects of ionizing radiation.

Post-radiation Changes of Saccharides

For saccharide compounds, the changes after irradiation will occur in both the solid state and in a solution. If radiolysis of saccharides is carried out in solid state, the radiolytic products depend on a crystalline form and the content of water. However, the products are not dependent on the atmosphere during irradiation. Saccharides are extremely sensitive to radiation in the crystalline state when the primarily localized energy is transferred to the crystal lattice. Thus, the radiation-chemical products of the reactions relate directly to the effect of energy transfer. The following physical-chemical changes can be observed in irradiated saccharides: reduction of melting point and changes of optical rotation. The absorption maximum is in the range from 260 to 285 nm and its intensity decreases with time. The products of radiolysis are as follows: H_2, CO, CO_2, H_2O, CH_4, formaldehyde, acetaldehyde, acetone, malonaldehyde, etc. Saccharide irradiation in the solid state gives rise to reactive compounds that may oxidize. This is demonstrated by a decrease of pH during dissolving irradiated sugar in oxygen-saturated water. The direct effect of radiation on saccharides in aqueous solutions is replaced by the indirect effect of the products of water radiolysis, in particular by the most reactive radical, i.e. hydroxyl radical. Similarly as for the radiolysis of saccharides in solid state, both the optical rotation and the index of refraction are reduced. The irradiation of aqueous monosaccharide solutions gives rise to H_2, CO, CO_2, formaldehyde, malonaldehyde, glyoxal, aldonic acid, uronic acid, sugar polymers and deoxy-compounds. Some substances, if in higher concentrations, could present a certain carcinogenic risk. The content of carboxyl acids increases in the presence of oxygen. During radiolysis of oligo- and polysaccharides, and in addition to the reactions mentioned above, the fission of the glycosidic bond also occurs. By irradiation of polysaccharides, for example starch, viscosity is reduced, and for higher doses the gel does not form. Starch grains become fragile and disintegrate, and starch exhibits an increased reactivity to α-amylase. If saccharide-rich food is treated by radiation, a small amount of the substances potentially hazardous to human health (e.g., formaldehyde, malomaldehyde and deoxysaccharides) may be formed. However, their concentrations are very low (in order of mg/kg for standard applicable radiation doses), and their content is reduced due to the effect of successive reactions with the other components in the presence of radical traps.

Post-radiation Changes in Fats

Fats are ranked among the less stable food components and hence very sensitive to ionizing radiation (Hammer and Wills 1979) that may induce many auto-oxidizing and hydrolytic reactions (Wills 1980) leading to undesired organoleptic changes and losses of essential fatty acids. Moreover, the arising peroxo-compounds may negatively affect other sensitive food components, for example, vitamins (Delinceé 1981). The range and the nature of all changes that were caused by certain radiation doses depend on the composition of the material to be irradiated, the type of fat and its content of unsaturated fatty acids (Wills 1980). The behaviour of different animal and plant lipids has been tested experimentally with the objective to find such fats that would manifest the highest stability during irradiation. The destruction of A-vitamin that belongs among the most sensitive substance to both the effects of ionizing radiation and the effects of auto-oxidizing processes (Coates et al. 1969) in fat has been selected as the criterion to assess the suitability of individual fats. Furthermore, the changes of the acid numbers and the peroxide numbers (Ford 1979) have been also assessed. From the results it is evident that irradiated animal fats seem to be more suitable compared to plant fats, mainly for their higher resistance against auto-oxidizing processes as indicated by the peroxide number.

Possible Use of Food Irradiation Technology

Food treatment by ionizing radiation is more frequently used for the sterilization of diets in many special cases of human nutrition. Such diets are mainly necessary for patients suffering from different disorders of the immune system, for example, tumours and AIDS (Aker 1984; Diehl 1990). Ionizing radiation may also be employed to treat diets for allergic patients. For example, by irradiation of milk proteins, the structure of their epitops can be destroyed so that their effects as milk allergens are reduced (Lee et al. 2001). Sterilized foods for the army and space flight use are also increasingly important (de Bruyn 2000; Rosado 2001). The process of exposure is more frequently used for the control of production in several types of raw or minimally processed foods, such as poultry, meat and meat products, fish, seafood, fruits and vegetables. In the production of these foods, irradiation may thus be a critical control point (CCP). It has the potential to eliminate vegetative forms of bacterial pathogens as well as parasites. Moreover, irradiation fulfils other criteria for a CCP, i.e., critical limits (minimum and maximum doses) can be established and monitored, and process control is well known (Molins et al. 2001).

Využití ionizujícího záření pro zabezpečení zdravotní nezávadnosti potravin

Ozařování potravin je velmi diskutovanou technologií. Tento proces má zajistit zdravotní nezávadnost potravin nebo jejich sterilitu, zabránit kažení potravin a snížit ztráty vznikající předčasným zráním, klíčením nebo škůdci. V České republice je nejčastěji ozařováno koření, kořenící směsi a sušená zelenina. V Evropě jsou největšími dodavateli ozářených potravin Belgie, Francie a Nizozemí. V USA je ozařování potravin daleko běžnější a je zde snaha uplatnit ho nejen k zajištění zdravotní nezávadnosti potravin, ale také k technologickým účelům. Přestože je ozařování potravin nadějnou technologií, její použití způsobuje fyzikálně chemické i biochemické změny, které mohou narušit nutriční hodnotu a senzorické vlastnosti ozářených potravin. V článku jsou popsány chemické změny základních složek potravin (bílkoviny, cukry, tuky). Výsledkem chemických změn jsou radiolytické produkty, jejichž rizikovost je stále předmětem vědeckého výzkumu. Předpokládá se využití technologie ozařování k ošetření diet pro pacienty s různými poruchami imunodeficitního systému, pacientů s alergiemi nebo pro armádu a vesmírné lety. Při produkci syrových a tepelně neošetřených potravin může být ozařování využito jako kritický kontrolní bod (CCP).

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