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MEDICAL PHYSICS AND BIOPHYSICS

Enhancement of Efficiency of Storage and Processing of Food Raw Materials Using Radiation Technologies

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Abstract—The work is dedicated to improvement of efficiency of storage and processing of food raw materials using radiation technologies. International practice of radiation processing of food raw materials is presented and an increase in the consumption of irradiated food products is shown. The prospects of using radiation technologies for the processing of food products in Russia are discussed. The results of studies of radiation effects on various food products and packaging film by γ radiation and accelerated electrons are presented.

Keywords: radiation processing, electron, accelerator, gamma, dose, standards, food products, microbiology, safety.

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INTRODUCTION

A rising tide of interest in radiation technologies as a basis for development of an innovation-driven economy has lately been registered in Russia. Application of radiation technologies in agriculture and the food industry is a worldwide trend [1]. According to the statistical data of the IAEA, more than more than 300 gamma-ray sources and more than 1500 accelerators used mainly for the processing of food products and sterilization are found at present in the world. The greatest number of accelerators are installed in the United States (more than 500 units) and in Japan (more than 300). Accelerators also predominate in the BRICS countries. An exception is India, where the number of gamma-ray sources exceeds the number of accelerators (17 vs. 4).

According to the data of the international commission of the Food and Agriculture Organization of the UN, the world losses of food products at all the stages of production reach 30%. Especially significant losses are observed in the case of fruit and vegetable products. The radiation processing of food products results in a delay in germination, disinsectization (insect disinfestation), the slowing of ripening processes, extension of storage time, and suppression of development of pathogens. Radiation technologies of the processing of food products are characterized by a high degree of efficiency, high performance, accurate radiation dosage regulation, possibility of processing packaged products, absence of high-temperature heating of the product and therefore possibility of sterilization of thermolabile products, and also low operating costs and conformity to the existing environmental standards.

RADIATION PROCESSING OF FOOD PRODUCTS

The radiation processing of food products is currently used in more than 40 countries of the world. In

2010, 285.2, 9.3, and 103 kt of food products were irradiated in Asia, the European Union, and the United States, respectively [2]. As compared to 2005, the amount of processed products increased by 100 kt in Asia and by 10 kt in the United States, while in the European Union, it decreased by 6 kt. According to the data of the International Commission on Radiation Protection, more than 200 kt of such products come into the market annually just in Europe.

Officially, the International Commission of FAO/WHO in 1983 approved the set of international food standards and rules for irradiation of food products up to 10 kGy. Up to the 1990s, national standards of the radiation processing of food products (spices, fruit, meat) and using radiation for insect sterilization were approved in economically developed countries (United States, France, Germany, etc.). In 1988, FAO, WHO, IAEA, and WTO negotiated the International Trade Agreement on Sales of Food Products Subjected to Radiation Processing. FAO and IAEA created a free online database of food products (Irradiated Food Authorization Database (IFA)) [3], in which the relevant data on irradiation of different food products were presented. It contained information from more than 60 countries on the given products or product groups: the aim of radiation processing, approval date, the minimum and maximum exposure doses.

In 1993, the American Medical Association (AMA) passed a resolution on safety and preservation of nutritional properties of products and beverages subjected to radiation exposure, and all tropical fruit exported into the United States from India, Mexico, Pakistan, South Africa, Thailand, and Vietnam have been subjected to radiation processing since 2006 to prevent spreading of insect pests. Growth of the market of radiation processing of agricultural and food products since the 2000s has been due to globalization and the increasing consumption and manufacture of food products and also high product losses at all processing chain stages. At present, the standards of radiation processing of food products are approved in the United States, Canada, and the European Union; these standards regulate the radiation processing procedures, packaging, and labeling of food products, radiation dosage control, and control of the processed products. The amount of such products in the world is consistently increasing. Thus, about 300 000 t of food products were treated in the world in 2005, while by 2010 this amount increased to 400 000 t. The IAEA actively promotes propagation of the practice of the radiation processing of food products [4]. The IAEA suggested special terms determining the degree of radiation processing with respect to agricultural products: radicidation (4–6 kGy), radurization (6–10 kGy), radappertization (10–50 kGy).

In the Soviet Union, studies on the possibility of the radiation processing of food products started at the beginning of the 1960s. Research was carried out at the Bach Institute of Biochemistry of the USSR Academy of Sciences, at scientific institutes of the All-Union Academy of Agricultural Sciences of the USSR, at the Research Institute of Nutrition of the Academy of Medical Sciences, and at the Erisman Research Institute of Hygiene. The performed studies [5, 6] demonstrated the promising outlook of application of the radiation method for prolongation of the shelf life of food products. Implementation of the radiation processing of food products in industrial technologies was delayed in the 1990s because of radiophobia and the emerging political and economic problems. This is the cause of the absence of fully elaborated licensing and controlling documents for radiation processing of food products. Atommed Center LLC is engaged in preparation of the modern regulatory framework in Russia. In 2011, this company prepared according to the order of the State Atomic Energy Corporation Rosatom 12 drafts of national standards of the Russian Federation on the radiation processing of food products. The main standards in the field of irradiation of food products are developed on the basis of the existing standards of providing radiation safety and standards approved in the European Union. ISO standards are being developed as part of the licensing documents for the Eurasian Customs Union of Russia, Belarus, and Kazakhstan.

In 2016, the GOST ISO 14470-2014 standard "Food irradiation. Requirements for the development, validation and routine control of the process of irradiation using ionizing radiation for the treatment of food" was introduced. The new standard provides observation of the most general requirements on organization of irradiation of food products that are used for improvement of the quality and safety of technologies of the processing of food products. This standard is intended for manufacturing facilities, radiation processing operators, regulators of activity, customers, and especially consumers. Approval of the remaining radiation processing standards is planned in the very near future.

SETUPS FOR RADIATION PROCESSING OF FOOD PRODUCTS

The radiation technologies of the processing of food products can be divided into two lines on the basis of the criterion of the ionizing radiation source. The first is based on using ionizing radiation from isotope sources and the second is exposure to high-energy electron beams from accelerators and electrophysical setups.

Cobalt-60 (^{60}Co) and cesium-137 (^{137}Cs) isotopes are the most widespread sources of γ radiation. Beta-emitting sources are used extremely seldom because of low penetrability. The penetrability of γ radiation is 50–100 times higher than that of electrons. Industrial sources of γ radiation based on cobalt tablets with nickel coating sealed in rod capsules of stainless steel are produced in Russia and abroad. These rods form grids used in the radiation processing of materials. ^{60}Co is synthesized by subjecting the single stable ^{59}Co isotope to neutron bombardment in a nuclear reactor. Cobalt sources have achieved a strong position in the market of radiation materials. For example, these are C-188 (MDS Nordion, Canada); RSL 2089 (PURIDEC, Great Britain); GIK-A3 (PO MAYAK, Russia); GK60CO2 and GK60CO3 (Scientific Research Institute of Atomic Reactors, Russia); and SB60 (Leningrad NPP, Russia). The largest producer of cobalt-60 in the world is MDS Nordion (Canada); it occupies more than 50% of the world market. The company is engaged in production and maintenance services for γ-sterilization complexes specifically for the purposes of radiation sterilization: JS-10000 Hanging Tote Irradiator; Parallel Row Pallet Irradiator; GammaBeam™-127 Irradiator. In Russia, the best known company is JSC NIITFA (Moscow); it manufactures radiotechnological setups based on the ^{60}Co isotope.

In recent decades, the interest of commercial organizations in sources of γ radiation based on isotopes has decreased because of high capital maintenance costs and difficulties related to handling radioactive materials and problems regarding utilization of spent elements.

Procedures based on electron accelerators are at present the most widespread in irradiation technologies [8]. As opposed to methods of sterilization by gamma radiation, electron radiation does not use radioactive isotopes. High-current electron accelerators appeared back in the 1950s, but their use was economically unjustified at the time. Gradually in-depth development of technologies of accelerated beams led to the possibility of increasing the energy, beam power (beam current), and current pulse length of the accelerated beam, and the costs of electron beam sterilization decreased to a quite acceptable level, which attracted interest of the food industry. Radiation processing occurs at electron energy ranging from 3 to 10 MeV. At such energies, the penetration depth of electrons proves to be sufficient for their penetration to a product packaged into shipment-ready containers. At present, it is allowed to use electron radiation with the energy of not more than 10 MeV and braking radiation generated by electron accelerators with the energy of not more than 5 MeV for the radiation processing of food products.

High electron radiation intensity allows using such irradiation for several seconds, as opposed to hours-long exposure of the product to gamma radiation. Short-term exposure to accelerated electrons reduces the possible effects of product oxidation and minimizes disruption of both the product and package material. The accelerators allow varying the energy of electrons and braking radiation. A decrease in the energy minimizes product damage as a result of radiation processing. The Budker Institute of Nuclear Physics, Siberian Branch, Russian Academy of Sciences (Novosibirsk); Efremov Research Institute of Electrophysical Equipment LLC (St. Petersburg); Korad Research and Production Enterprise (St. Petersburg); Torii Research and Production Enterprise (Moscow); Skobeltsyn Research Institute of Nuclear Physics, Moscow State University (Moscow); Moscow Radiotechnical Institute, Russian Academy of Sciences (Moscow); National Research Nuclear University (Moscow Engineering Physics Institute) (Moscow); Tomsk Polytechnical University (Tomsk); Institute of High-Current Electronics, Siberian Branch, Russian Academy of Sciences (Tomsk); Institute of Electrophysics, Ural Branch, Russian Academy of Sciences (Yekaterinburg); Russian Federal Nuclear Center All-Russian Research Institute of Experimental Physics (Sarov); and Keldysh Research Center (Moscow) are engaged in development of industrial electron accelerators. Since 1980, more than 200 accelerators have been designed and installed in Russia for implementation of industrial radiation technology processes (without taking into account accelerators for medicine, flaw detection, and tomography). At present, more than 60 linear electron accelerators are in service [8]. One must point out that the running costs of a modern accelerator and capital costs of construction of a radiation accelerating center are lower than those of radiation complexes based on isotope sources.

About 12 radiation technology complexes (RTCs) are active at present in Russia; of these, only seven are on an industrial scale; the average annual number of sterilized products includes more than 250 types of disposable medical articles with the overall amount of approximately one billion units. A test treatment of small amounts of dried fruits, spices, and fish products is performed at some of them. Of the seven industrial-scale RTCs, two require recharging of the ^{60}Co sources. Five RTCs have been working for more than 20 years; they are physically obsolete and are working in the "periodic maintenance" mode and will be stopped in the years to come. Thus, with Russia entering WTO and approving the new ISO GOST standards, demand will appear for creating new RTCs based on electron accelerators for the processing of food products of a wider spectrum. Thus, in 2013, the commercial company Tekleor LLC was founded, and it is engaged in constructing an RTC in Kaluga oblast at the border with Moscow oblast for the industrial processing of food products.

STUDIES OF RADIATION EXPOSURE OF FOOD PRODUCTS IN RUSSIA

In 2010, interest in using radiation technologies in the food industry in Russia started increasing again. It was stated in the meeting of the Science and Engineering Council of Rosatom on August 11, 2010, on the topic "Development of Radiation Technologies for Agriculture and the Food Industry" that using ionizing radiation is one of the priority methods in the food industry.

In 2013, a collaboration was created around the All-Russia Research Institute of Preservation Technology (VNIITeK) for performing research in the field of using radiation technologies in the food industry. VNIITeK has accumulated a lot of experience in performing research on this subject. In the 1970s, the All-Russia Research Institute of Preservation Vegetable Drying Technology (at present, VNIITeK) studied under the direction of V.I. Rogachev and M.L. Frumkin the radiation exposure of raw materials and products of plant (fruit, berries, vegetables) and animal (meat, processed meat) origin and also ready-to-serve foods. Studies were carried out using setups equipped with different radiation sources: the electron accelerator and the gamma setup (Bogucharovo, Tula oblast) that was a stationary pilot experimental setup based on ^{60}Co with the radiation source activity of 300 Ci. Since 2013, VNIITeK has conducted yearly seminars (panel discussions) dedicated to the problems of using radiation technologies for the processing of agricultural raw materials and food products.

The members of collaboration were organizations possessing radiation complexes: Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences (IPCE RAS), and NIITFA. Starting in 2011, studies of the radiation exposure of food products employing the experimental base of these organizations were renewed at VNIITeK. In 2013, the collaboration was joined by the Russian Research Institute of Baking Industry and the Russian Research Institute of Confectionery Industry. In 2013, experts from VNIITeK participated as associate contractors in Federal Target Program "Studies and Development on Priority Directions of Development of the Scientific and Technological Complex of Russia for 2007–2013" (lot 2013-1.2-14-512-0033 "Studies of Biological Efficiency of Exposure of Living Systems to Ionizing Radiation"). The leading organization was the All-Russia Research Institute of Agricultural Radiology and Agroecology, Russian Academy of Agricultural Sciences, which had a source of gamma radiation based on cobalt-60. Realization of the project yielded data on extending the storage time without loss of organoleptic quality of fruit and vegetable products packaged in polymer film [10].

The UELV-10-10-S-70 accelerator (energy of 10 MeV, beam power of 10 kW), a multipurpose source of ionizing radiation intended for application in industrial radiation technology processes was used in studies at the Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences (IPCE RAS). The dosage rate of electron radiation at the distance of 1 m from the outlet port flange is 3 kGy/s. A rotary transfer is used in the accelerator for transport of the irradiated samples. Many studies of radiation exposure of pure microorganisms to accelerated electrons were carried out using this accelerator, together with the Russian Research Institute of Baking Industry (VNIIKhP) [11]. In [11], radiation resistance D_{10} was determined, which was 0.8 kGy for lactic acid bacteria and 1 kGy for yeasts. This allowed estimating inactivation of these microorganisms by irradiation of foodstuffs impregnated with these cultures. It was found that radiation resistance D_{10} of many microorganisms was several kilogray and irradiation to comparatively small doses could achieve reduction of the concentration of microorganisms in the food.

Studies have also been also carried out using radiation complexes of the Research Institute of Technical Physics and Automation (NIITFA), which has a U-003 Elektronika electron accelerator with the energy of 5 MeV and average beam current of 650 μA and a GU-200M gamma setup with the maximum ^{60}Co activity of 200 kCi. Since 2013, many studies of radiation exposure of dry spices (khmeli suneli, powdered cilantro), straight white wheat flour, ground nuts, and samples of multilayer polymer films for food product packaging have been carried out on these setups.

Experimental studies for control of the absorbed dose used film detectors based on the chemical method of SO PD(F)R-5/50 and SO PD(E)-1/10. Film detectors were manufactured according to TU 2379-006-1327176-00 at the Doza Research and Development Enterprise. These dosimetric films were certified at Rostest-Moscow and were tested by the All-Russia Research Institute of Physicotechnical and Radiotechnical Measurements (VNIIFTRI), Mendeleevo, Russia. The detectors were placed on the irradiated samples and then the absorbed dose was determined using a Varian Cary 100 Scan spectrophotometer at VNIITeK by comparing the values of the optical density with respect to the reference sample. The errors of determining the dose using the SO PD(F)R-5/50 and SO PD(E)-1/10 detectors do not exceed 12% and 15%, respectively.

Studies of radiation exposure of straight white wheat flour and ground nuts were carried out at NIITFA in collaboration with the Russian Research Institute of Confectionery Industry (VNIIKP). The amount of initial and surviving microorganisms was determined using the following techniques: the amount of mesophilic aerobic and facultative anaerobic microorganisms was determined using GOST 10444.15-94; the amount of mold and yeasts was determined using GOST 10444.12-88; the presence of bacteria of the *E. coli* group (coliforms) was determined using GOST R 52816-2007. Products were processed in polymer film packages in a 5 cm layer with different dosages of gamma radiation and the quantitative and qualitative changes in microbiota were determined. The lethal dose for sanitary indicator microorganisms was 2.0–2.5 kGy for straight white wheat flour and 3.3–3.7 kGy for nuts. Thus, the technological parameters for irradiation of food product lots were determined.

In 2015, the effect of the given radiation dosages on dry flavors and spices was studied. The studied objects were powdered khmeli suneli and ground dry cilantro. Dry flavors were packaged in polymer bags and cardboard boxes with the weight of 4.94 kg (khmeli suneli) and 3.360 kg (cilantro). The aim of radiation processing of the samples was to decrease the concentration of microorganisms to the level corresponding to the requirements of Technical Regulations of the Customs Union 201/2011. Contamination of the supplied samples before and after processing was determined according to GOST 10444.15-94 and GOST 28805-90. The humidity of the samples was 5–7% (powdered khmeli suneli) and 4–6% (dry ground cilantro).

Irradiation was carried out using the radiation technology setups of NIITFA. The obtained curves of a decrease in the concentration of microorganisms allowed estimating radiation resistance D_{10} of microorganisms, which was 2 kGy for the ^{60}Co gamma setup and 3kGy for the electron accelerator. The minimum radiation dose required for inactivation of microorganisms was 4–6 kGy. With allowance for the implied nonuniformity of product contamination in the package and nonuniformity of the exposure dose in the package, the maximum required exposure dose was 10–12 kGy. For this dose, no change in physicochemical indicators and organoleptic quality of products was registered. One can see from comparison of the results of decontamination of ground cilantro and powdered khmeli suneli with the data from the ASTM standard [12] that the recommended minimum exposure dose for some spices, herbs, and vegetable flavors are similar to the dose values obtained in the study.

At present, the food industry uses multilayer film materials of different composition to increase the shelf life of fresh fruit and vegetables. VNIITeK and NIITFA performed experimental studies of the effect of irradiation on the molecular structure of multilayer films. The materials used in the study were polyamide/polyethylene (PA/PE = 80 : 20) polymer package material with the thickness of 80 μm (Dmitrov Flexible Packaging Plant (DFPP)) and film packaging material.

Samples were subjected to irradiation to doses of 3 to 18 kGy. The sample structure before and after irradiation was studied using IR spectroscopy techniques. IR spectra were measured using an FMS 1201 device. The spectral range was 400–4000 cm^{-1}; the spectral resolution was 1 cm^{-1}; the source of the IR flux was Nichrome; the IR flux receptor was pyroelectric. Studies of tensile strength and breaking elongation of samples before and after irradiation was carried out in [13] using a Zwick 1445 device. Tests were performed in the lateral and transverse directions of the samples with the width of (10.0 ± 0.1) mm at the temperature of (23 ± 2)°C and relative humidity of (50 ± 5)%.

Studies of the structure of multilayer polymer PA/PE materials before and after gamma irradiation showed that no significant changes occurred in the samples at the doses of 3 kGy [14]. An increase in the dose led to cross-linking and destruction processes, which could result in changes in physicomechanical and barrier properties of the polymer material. Studies of mechanical properties of samples showed that the statistics of the processed experimental data did not reveal any existing difference in the samples before and after the processing owing to wide confidence ranges. These conclusions are preliminary and statistical data still are to be accumulated.

CONCLUSIONS

The paper considers the issues of using radiation processing for enhancement of the storage time of agricultural goods and the modern legal framework regarding radiation processing. The possibilities of using the radiation centers already present in Russia for the irradiation of food products are analyzed. The results of studying the radiation processing of food products and package materials are briefly presented.

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