Irradiation influence on the chemical composition and morphological properties of the agricultural products

E N Anikieva¹, A Yu Astapov¹, A A Anikiev² and E A Anikieva³

¹Michurinsk State Agrarian University, 101, International st., Michurinsk, 393760, Russia
²Bauman Moscow State Technical University, 2-ya Baumanskaya line, 5, Moscow, 105005 Russia
³Rosenergoatom, 25 Ferganskaya ave., Moscow, 109507 Russia

E-mail: korol_0909@mail.ru

Abstract. The article discusses the impact of radiation treatment of agricultural products on their chemical composition, which determines the nutritional value of products, as well as on the main properties of products. The main advantages of agricultural products that have undergone radiation treatment are given, related, inter alia, to an increase in their shelf life, prevention of diseases and insect damage. The world experience of increasing the volume of radiation processing products by type in comparison with the 2010 level is considered. The main criteria for radiation processing of food products and the levels of radiation doses required for absorption by products to achieve certain technological goals are presented. The influence of radiation doses of radiation on proteins, fats, carbohydrates and vitamins in agricultural products is indicated. The influence of radiation exposure on the growth and maturation of some crops is estimated. The possibility of the influence of changes in the structure and composition of irradiated food products on the human body is emphasized. The factors that ensure the profitability of farms that use the practice of radiation processing of agricultural products when supplying them to international markets are also given. The calculations are carried out on a model of a small farm specializing in the cultivation of cucumbers and tomatoes.

1. Introduction

Agriculture as the core of the agro-industrial complex solves the problem of timely and full-fledged supply of the population, retail and wholesale trade networks with livestock and crop products, while increasing the country's security level, as it makes it less dependent on price fluctuations in world markets. At the same time, any of the countries playing a definite role in the agricultural market, being a part of the world economy, exports agricultural products to other countries, and also imports products from other countries. Accordingly, the quality, "purity", safety and range of products supplied by agricultural enterprises in other countries play a decisive role in ensuring the standard of living of the population [1-4].

One of the methods of ensuring the safety and improving the quality of agricultural products produced in our country and supplied from other countries is radiation exposure.

According to the IAEA, there is an increase in interest in agricultural radiation technologies all over the world. Taking into account the steady tendency to spoilage of about a third of all world food...
products produced annually [5], the application of these technologies to agricultural products allows one to overcome a wide range of problems leading to premature aging and death of products, allowing one to achieve the following results:

- extension of shelf life (inhibition of ripening in terms of fresh fruits and vegetables, delay in germination of potatoes, tuber and root crops by irradiation);
- assistance in the fight against insect pests by pest control;
- prevention of seed diseases (substitution of chemical dressing);
- increasing the productivity of crops;
- feed processing and waste disinfection.

At the same time, despite the conflicting reviews regarding the radiation processing of food, based on a long-term analysis of data from the leading countries of the world on the possible toxic effects of radiation on food, the World Health Organization proved the harmlessness of food products irradiated with a dose of no higher than 10 kGy. At the same time, irradiation of food products with the absorbed dose above 10 kGy should be properly justified and subject to official documentation [6].

The analysis of the world experience in the application of radiation technologies for food processing showed [7, 8] that in 69 countries it is officially allowed one to irradiate more than 80 types of products, about 40 countries carry out radiation processing on an ongoing basis [9]. Table 1 shows statistics on the volume of radiation processed products in 2015 in comparison with the level of 2010 in various countries [10].

Table 1. Radiation treatment volumes of products in 2015 compared to 2010

| Name of the country       | Types of products that have undergone radiation treatment                                    | Volume of processed products, thousand tons |
|---------------------------|------------------------------------------------------------------------------------------------|------------------------------------------|
|                           |                                                                                              | 2010          | 2015          |
| South Africa              | Spices, pickles, commeal, honey, beeswax, garlic, ginger, fruits, vegetables, dried fruits, grapes, nuts, seafood, meat, raisins | 19            | 23.5          |
| United States of America  | Spices, fruits, vegetables, meat, shrimp, poultry                                           | 21.75         | 130.5         |
| Canada                    | Whole and ground spices and dehydrated seasonings                                            | 0.95          | 1.25          |
| Hawaii                    | Longan, rambutan, sweet basil, dragon fruit, papaya, banana, mango, sweet potato             | 0.53          | 0.65          |
| Mexico*                   | Guayava, mango, chili, lime, dragon fruit, pomegranate                                       | 5.65          | 11.7          |
| China                     | Garlic, spices, grain, meat, chicken legs, etc.                                              | >266          | >600          |
| India                     | Mango                                                                                       | 0.2           | 0.7           |

* For Mexico, the volume of exports to the United States of radiation processed products is indicated.

As it is seen from the table above, African countries, North American countries, and Asian countries are increasing the volume of products (including for export purposes) that have undergone radiation treatment.

2. Materials and methods

We will look at two major competing and decisive factors in the use of radiation technology for agricultural processing. The first factor is economic, we will study it on the model of increasing the productivity of crop farms using radiation processing of produced vegetables. The second factor - the influence of ionizing radiation on the microstructure, chemical composition and morphological properties of plant products, as well as the influence of the influence of irradiated products on the human body - will be described based on the results of studies carried out by that time. This factor lends itself to analysis and calculations, based on the existing experience of using ionizing radiation to increase the duration of food products, food products around the world (Table 1), then the analysis of
the world of the second factor is at the initial stage of the need for a detailed and comprehensive study, based on methods and advances in radiobiology.

**Factor 1.** The main and defining criterion for radiation processing of food products is the established relationship between the absorbed dose of the product and the parameters of the radiation processing plant, depending on the goal (increasing the storage period, processing and destroying parasites, preventing infection and the development of diseases). Table 2 presents data on the required ranges of absorbed doses during irradiation of food and agricultural products (analysis of world practices), depending on the purpose of treatment [11].

**Table 2.** Data on the required ranges of absorbed doses during food irradiation depending on the purpose of treatment

| Technological purpose of radiation treatment (effect of exposure to ionizing radiation) | Dose range, kGy D<sub>max</sub>/D<sub>min</sub> | D<sub>max</sub>/D<sub>min</sub><sup>1</sup> |
|---|---|---|
| Delayed germination of bulbs and tubers | 0.03-0.15 | 0.03-0.1 | 3-5 |
| Insect disinfection | 0.15-0.5 | 0.03-0.2 | 3-6 |
| Destruction of parasites | 0.25-1.0 | 4 |
| Improvement, acceleration of fruit ripening | 0.03-0.15 | 5 |
| Prevention of infestation by insects, parasites | 0.07-1.00 | 1-1.3 | 14-1.3 |
| Delaying rotting and spoilage of meat | 1.50-3.00 | 2.0-7.0 | 2-3.5 |
| Increased shelf life (meat, berries, mushrooms, etc.) | 1.0-3.30 | | 3.3 |
| Reducing the risk of contracting disease-causing microorganisms | 1.00-7.00 | | 7 |
| Increased sanitation for spices and herbs | to 10.00 | | 3 |
| Sterilization of packaged meat | 25-70 | | |
| Sterilization (meat, seafood, poultry, etc.) | 30-50 | | 1.6 |
| Disinfection of individual additives and ingredients | 10-50 | | 5 |

From the point of view of wholesale and retail buyers, agricultural products that have undergone radiation treatment have a number of advantages:

- longer shelf life, allowing one to minimize product losses with timely sale;
- possibility of purchasing large volumes of batches of products and reducing the logical costs of their transportation;
- absence of insect pests, the mechanical action of which leads to premature spoilage;
- reduction of negative responses of buyers to low-quality, not properly processed, perishable products.

These factors create opportunities for wholesale and retail consumers of agricultural products to increase additional profits in the form of cash flows from new buyers, and also lead to a decrease in the costs of disposal of spoiled products. In turn, the interest of such consumers in radiation-processed products is growing, and, as a result, analogue products with lower prices, but not undergoing the specified processing, look less attractive to them. Thus, an increase in prices by agricultural enterprises for radiation-processed products within the limits of inelastic demand will allow such enterprises to increase the profitability of their business both in terms of the volume of products sold and in terms of reducing losses during storage.

**Factor 2.** From the point of view of the effect of ionizing radiation on plant organisms, the following problems have not yet been solved [16]:
- the effect of ionizing radiation on the stimulation and inhibition of biological processes at various levels of the organization of the biological system;
- the effect of ionizing radiation on DNA, restorative and antioxidant systems, which affect radiation stimulation and suppression of biological processes, has not been sufficiently studied;
- there is no clear understanding of the temporal evolution of the transcriptional activity of genes and changes in the ratio of phytohormones at the initial stages of ontogenesis and during long-term storage of seeds and roots exposed to radiation;
- no regularities of the effect of ionizing radiation on the system "products - parasitic and pathogenic organisms" have been identified, there is no data on the dynamics of the population size of various types of parasitic and pathogenic organisms in the process of storing raw materials and finished agricultural products.
- insufficient information to assess the possibility of irradiation of fresh fruits and vegetables - the products most sensitive to the effects of ionizing radiation.

Conclusions about the nutritional value of products that have undergone radiation treatment can be drawn by analyzing the change in their chemical composition in terms of transformation of basic compounds. Fresh fruits and vegetables - products with a high concentration of water - are especially exposed to ionizing radiation. This directly applies to the products considered by the example of factor 1 - tomatoes and cucumbers (up to 90% water).

3. Results

**Factor 1.** We considered an example of increasing the profitability of a farm located in the Moscow region and selling radiation-treated tomatoes and cucumbers.

The following scenario is proposed for calculating the volume of products produced by a farm and assessing profits when taking into account the radiation processing of manufactured products:

- Planning horizon, years - 2021-2030;
- Total area of the farm, hectares - 2, of which 1 - for tomatoes, 1 - for cucumbers;
- Tomato yield, kg / sq. m - 4;
- Barrel cucumbers yield, kg / sq. m - 10.5;
- Product losses without radiation treatment, % per kg - 10;
- Product losses after radiation treatment, % per kg - 2;
- The cost of food irradiation (average minimum), rubles / kg - 10 rubles per kg [10];
- Tomato sales volume (excluding losses), kg - 40,000;
- Barrel cucumbers sales volume (excluding losses), kg - 105,000;
- Tomato price (average price for 2019), rubles / kg - 84.9 [12]
- Barrel cucumbers price (average price for 2019), rubles / kg - 77.3 [12]
- Estimated increase in sales of radiation-treated products, % per year - 3;
- Inflation, % per year – 4;
- VAT, % per year - 20;

The calculation procedure is reflected in the tables in Appendices 1 and 2.

Based on the calculations, we have built graphs that clearly reflect the advantages of radiation processing of products in relation to the profit of a small farm.

The figure shows a comparative analysis of the net profit of a farm depending on the presence / absence of radiation processing, performed according to the proposed scenario. Tables with the calculation results are given in the appendix to the text of the article.
As can be seen from the figure, with additional costs for processing tomatoes and cucumbers, an annual increase in product sales due to increased consumer demand (excluding the additional increase in food prices dictated by processing costs), as well as a decrease in the amount of product losses during storage, will lead to a significant increasing the net profit of the farm in the period of 2021-2030. The total volume of net profit for the period under consideration, subject to the sale of radiation-treated products, will amount to 135,568 thousand rubles, which is 105.6% more than the net profit received from the sale of products that have not undergone radiation treatment.

**Factor 2.** Water molecules are excited and ionized to a much greater extent than other components of the composition. It is known that excited and ionized water molecules form free hydroxyl radicals, hydrated electrons and hydrogen atoms. They, being the main products of water radiolysis, determine the chemical effect of irradiation. The water radiolysis reaction in a simplified form is as follows [17]:

\[ H_2O \rightarrow 2,7OH^- + 2,7e^{-}_{hydr} + 0,55H^+ + 0,45H_2 + 0,71H_2O_2 + 2,7H_3O^+ . \]

Here \( OH^- \) and \( H^+ \) are neutral free hydroxyl radicals and hydrogen atoms, \( e^{-}_{hydr} \) is a hydrated electron; other three components of the reaction are molecular hydrogen, hydrogen peroxide and hydrogen ions.

Hydroxyl radicals react with a large number of organic compounds, resulting in the formation of organic free radicals. Hydrated electrons react with most aromatic compounds, amino acids, carboxylic acids, aldehydes, disulfides, forming molecules of new organic compounds and free organic radicals. Chemical reactions with the participation of atomic hydrogen have a similar effect.

The presence of free organic radicals in irradiated foods causes various reactions. They can reduce minor components, interact with oxygen to form peroxide radicals, decompose to form new radicals, causing a chain reaction; react with each other to form new products.

Studies of the effect of ionizing radiation on food, carried out under the auspices of the IAEA and other organizations promoting methods of radiation treatment of agricultural products, do not see a significant effect on the nutritional value of radiation in doses taken as not having a significant effect on the destruction of valuable nutrients. So, for example, according to the results of reports [7, 8], vitamins in food are better preserved after irradiation. The degree of radio resistance of various vitamins depends on the chemical composition of the products in which they are found. For example, the percentage of destruction of carotene at a dose of 20 kGy will be 60-80%, while the percentage of
destruction of vitamin E at a dose of 30 kGy in meat (when irradiated in an oxygen atmosphere) will be 60% [18]. Vitamin K in spinach has an insignificant percentage of destruction at doses of 50 kGy. Vitamins B12, B2 and B3 have the least degree of destruction after radiation treatment [18]. At the same time, vitamin C and thiamine have less resistance.

The biological value of protein compounds of almost all food products (with the exception of milk and peas) after radiation treatment changes at the level of other types of processing. In this case, the compounds arising from irradiation of proteins and amino acids do not possess toxic and carcinogenic properties.

Under the influence of radiation exposure, carbohydrates are converted from complex compounds to simpler ones, to a greater extent due to the rupture of glucoside bonds. At the same time, the nutritional value of carbohydrates practically does not change after irradiation. In some cases, its increase is observed due to the conversion of complex carbohydrates into simpler and more digestible [18].

Radiation doses in the range of 10-50 kGy [17] have no significant effect on the main characteristics of lipids. Thus, the viscosity, caloric content, assimilability of fats and oils within the indicated limits of kGy do not change significantly. Melting points are less susceptible, their density and the number of double bonds remain practically constant.

Thus, it can be concluded that proteins, carbohydrates and fats are damaged by radiation to an insignificant extent. A number of vitamins are prone to degradation when treated with radiation, depending on the type of product, the conditions of irradiation and storage. These features must be taken into account when planning economic activities, for example, by wholesale and retail trade networks that sell food products.

However, you should pay attention to the following processing consequences. Under the influence of radiation, toxic compounds, such as acetaldehyde, acetone, formaldehyde, formic acid, benzene, toluene, hydrogen sulfide, dimethyl disulfide, accumulate in the products in small amounts, which do not cause instant poisoning of the human body. However, some of these compounds have the ability to accumulate in the body and then manifest themselves in the form of chronic poisoning, cause mutagenic, carcinogenic and other adverse effects.

Radiation exposure methods are widely used not only at the final stage of product "maturation". Thus, the pre-sowing irradiation of agricultural seeds contributes to the acceleration of germination, development and an increase in plant productivity. Table 3 presents the average data on the increase in the yield of agricultural crops under irradiation of seeds [19].

From the point of view of the chemical composition of the irradiated crops, pre-sowing irradiation can increase the quantitative content of certain substances and affect the formation of new compounds. To date, the appearance of toxic properties in agricultural crops that have undergone radiation treatment during the period of their storage and in remote periods has not been studied in detail.

At the same time, pre-sowing treatment of agricultural crops affects such properties of products as growth time, fiber strength and length, ripening period. Thus, stimulating the growth of plants such as flax, hemp and cotton has led to an increase in fiber length and strength. The ripening period under the influence of radiation is also shortened by several days - a week. For example, for some types of vegetable crops, such as cucumbers, the ripening period can be reduced by 5-10 days [19].

Thus, the treatment of food products with ionizing radiation has both its positive and negative sides.
Table 3. Average data on the increase in the yield of agricultural crops under irradiation of seeds

| Crop name           | Stimulating dose, Gy * | Increase in yield to control, % |
|---------------------|------------------------|---------------------------------|
| Corn for grain      | 5-10                   | 110-115                         |
| Silage corn         | 5                      | 110-130                         |
| Wheat               | 5-8                    | 109-111                         |
| Barley              | 10-30                  | 107-115                         |
| Buckwheat           | 5-7                    | 115                             |
| Sunflower           | 10                     | 110-120                         |
| Millet              | 5-10                   | 115-140                         |
| Peas                | 3                      | 115-140                         |
| Lupine              | 10                     | 118-127                         |
| Rye                 | 5                      | 112-114                         |
| Clover              | 5                      | 130                             |
| Alfalfa             | 10                     | 115-120                         |
| Cotton              | 10                     | 110-120                         |
| Cabbage             | 20                     | 113-120                         |
| Tomatoes            | 5-10                   | 110-115                         |
| Radish              | 10                     | 115-120                         |
| Carrot              | 25-40                  | 125-135                         |
| Cucumbers           | 3                      | 110-140                         |
| Sugar beet          | 10-20                  | 115-120                         |
| Rice                | 5-20                   | 110-112                         |
| Beans               | 7.5-10                 | 110                             |
| Sorghum             | 5                      | 110-120                         |
| Soy                 | 7.5                    | 112-117                         |
| Linen               | 7.5                    | 112                              |

* stimulating doses for different varieties of crops and in different soil and climatic conditions

4. Discussion

When considering the first - the economic factor, it is necessary to pay attention to the fact that we gave an example of a small farm. Large agricultural complexes, having significantly greater financial capabilities, can independently purchase equipment for processing products with ionizing radiation and hire certified specialists to work with it.

In this case, the profit of the enterprise will grow significantly and non-linearly after the cost of purchasing the equipment is paid off.

Nevertheless, as shown by consideration of 2 factors, along with advantages, there are also a number of disadvantages of radiation exposure of products. First of all, these are the risks of a decrease in consumer demand due to the natural fear of buyers to purchase products subjected to radiation treatment. Secondly, radiation exposure of products, especially fresh vegetables and fruits, even in doses safe for humans, leads to a change in the microstructure, morphological and organoleptic properties of products, which can affect consumer demand. Thirdly, the long-term effect on the body of the consumption of foods exposed to radiation has not been studied. In addition, there are a number of works [13-15] whose authors are very ambiguous about the methods of radiation exposure of food products due to the possibility of the formation of mutagenic substances and toxins in them as a result of irradiation.

5. Conclusions

The all-season supply of the population of countries around the world with fresh vegetables and fruits growing in regions from northern to equatorial and tropics poses special requirements for the phytosanitary processing of these types of products. From this point of view, the protocols for
phytosanitary treatment with ionizing radiation provide for 15 treatments against 13 types of insect pests. In addition to direct effects in relation to phytosanitary measures, radiation exposure at certain doses prevents spoilage of products, allowing a high level of product quality to be maintained, preventing premature germination and ripening of vegetables and fruits. In our opinion, radiation treatment measures are becoming more and more relevant in connection with the tightening of phytosanitary treatment measures and allow farmers to receive additional profits by expanding the trade markets for their products, minimizing losses and waste. Currently, more than 60 countries have adopted international standards allowing the use of radiation for a number of food products in doses that do not lead to sterilization of the product. The preliminary calculations of the economic efficiency of radiation exposure performed in this work according to the set scenario show that even under the most unfavorable conditions, inflation, low purchase prices and average demand, radiation exposure can increase the net profit of a small farm by an average of 100% over a period of 8-10 years.

At the same time, there are a number of factors based on the principles of radiobiology, showing contradictions in the principles and methods of processing food products with ionizing radiation. For example, radiation doses leading to the destruction of insect pests, suppression of populations of parasitic and pathogenic organisms are hundreds and thousands of times higher than doses that do not lead to a change in the microstructure, morphological and organoleptic properties of food products, especially with regard to fresh fruits and vegetables. In addition, the obvious economic benefit of radiation treatment should not influence the study of unfavorable factors of changes in the structure of compounds included in the composition of products that affect the ability of the human body to assimilate them.

The process of assimilating plant food refers to such metabolic processes in which the chemical structure of the components of the product must correspond to the enzyme systems of the body. Quantitative violations of this correspondence lead to food intolerance and, as a result, to various forms of allergies. However, this is the least possible impact. Consumption of products containing peroxides contributes to the accumulation of toxic substances resulting from lipid peroxidation in cells, which leads to a change in the properties of membranes up to their degradation and impact on the genetic apparatus of the cell. Consequently, the effect of ionizing radiation on the structure and properties of food products, and through them the impact of these products on humans, requires a comprehensive study to develop standards and conditions for radiation processing. Moreover, these studies should be carried out continuously and regardless of affiliation with organizations that promote the means and methods of radiation processing of food products on the market.

References
[1] Rudik F Ya, Morgunova N L and Krasnikova E S 2020 Decontamination of grain by ultrasound IOP Conference Series: Earth and Environmental Science 421(2) 022022
[2] Ivanova E S, Rodionovich Y V, Ivanova E P, Konovalov V V and Nikitin D V 2020 Research of methods of processing post-spirit drinking enterprises of the central-black-earth district IOP Conference Series: Earth and Environmental Science 422(1) 012112
[3] Brizhanskij L V, Brizhanskaya Yu A, Lasica A M and Dorohova A M 2020 Effect of low intensity laser radiation on sugar content in sugar beet root crops obtained from seeds treated with a quantum generator Journal of Physics: Conference Series 1679(2) 022026
[4] Perfilova O V, Babushkin V A, Blinnikova O M and Bryksina K V 2020 Physical methods in innovative technological solutions of beet refuse processing Journal of Physics: Conference Series 1679(4) 042031
[5] Sanzharova N I, Geraskin S A, Isamov N N, Kolmin G V, Loy N N, Pavlov A N, Pimenov E P and Tsigvintsev A N 2013 Scientific basis for the application of radiation technologies in agriculture (Obninsk: VNIISKHRAE) 133 p
[6] Gromov A A, Zhanzhora A P, Kovalenko O I and Tenoshev V P 2018 Food processing by ionizing radiation in the Russian Federation Radiation technologies in agriculture and food industry:
state and prospects. Collection of reports of the international scientific and practical conference pp 151-154

[7] Harder M N C 2016 Irradiation of Foods: Processing Technology and Effects on Nutrients: Effect of Ionizing Radiation on Food Components, In: Harder M N C, Arthur V, Arthur P B Encyclopedia of Food and Health (Oxford: Academic Press) pp 476–481. doi: 10.1016 /B978-0-12-384947-2.00405-0.

[8] 2015 Manual of Good Practice in Food Irradiation/ Sanitary, PhytoSanitary and Other Application Technical Reports series No. 481 (Vienna: International Atomic Energy Agency)

[9] Sommers C H and Fan X 2006 Food irradiation research and technology (Blackwell Publishing Professional) 317 p

[10] Global Status and Commercial Applications of Food Irradiation. Retrieved from: http://foodirradiation.org/Global%20Status%20of%20Food%20irradiation.pdf

[11] Petrova N V and Tenoshev V P 2018 Provision of safe food and agricultural products during processing by ionizing radiation Materials of the International Scientific and Practical Conference «Radiation Technologies in Agriculture and Food Industry: Current State and Prospects» pp 169-171

[12] Rosstat. Retrieved from: https://rosstat.gov.ru/price

[13] Li X and Farid M 2016 A review on recent development in non-conventional food sterilization technologies Journal of Food Engineering 182(2) 33–45. doi: 10.1016 / j.(foodeng. 2016.02.026.

[14] Siddhuraju P, Makkar H P and Beckera K 2012 The effect of ionizing radiation on antinutritional factors and the nutritional value of plant materials with reference to human and animal food Food Chemistry 78 187–205. doi: 10.1016 / S0308–8146 (01) 00398–3.

[15] Honda H, Ogawa M, Murakoshi T, Masuda T, Utsumi K, Nei D and Wada Y 2015 Variation in risk judgment on radiation contamination of food: thinking trait and profession Food Quality and Preference 46(7) 119–125. doi: 10.1016 / j.foodqual. 2015.07.014.

[16] Sanzharova N I, Kozmin G V, Bondarenko V S 2016 Radiation technologies in agriculture: strategy of scientific and technological development Innovation and expertise 1(16) 197–206

[17] Elias P S and Cohen A J (Eds) 1983 Radiation chemistry of the main components of food (Moscow: Light and food industry) 224 p

[18] Pavlov Yu S, Petrov A N, Trishkanova M V, Fedyanina N I, Mishurov N P and Nemenshaya L A 2019 Radiation methods in crop processing. Scientific analytical review (Moscow: Rosinformagrotech) pp 31-33

[19] Gudkov I N 1991 Scientific Foundations of General and Agricultural Radiobiology. Retrieved from: http://booksshare.net/index.php?id1=4&category=biol&author=gudkoev&book=1991&page=1.