RUDN Journal of Agronomy and Animal Industries. ISSN 2312-797X (Print). ISSN 2312-7988 (Online)
Вестник РУДН. Серия: АГРОНОМИЯ И ЖИВОТНОВОДСТВО
2023;18 (4): 541—553
http://agrojournal.rudn.ru

Защита растений
Plant protection

DOI: 10.22363/2312-797X-2023-18-4-541-553
EDN: MNPTDN
UDC 632.08

Review article / Обзорная статья

World experience in the application of low-energy electron irradiation in agriculture

Oksana V. Tkhorik, Vladimir A. Kharlamov ✉, Irina V. Polyakova, Nadezhda N. Loy, Maria G. Pomyasova, Valentin I. Shishko

Russian Institute of Radiology and Agroecology of National Research Centre «Kurchatov Institute», *Obninsk, Russian Federation*
✉ kharlamof@gmail.com

Abstract. According to the long-term observations of the FAO, losses of plant-based agricultural products are estimated to be between 10 and 30 %. The main causes of these losses are plant pathogens, spoilage microorganisms, and insect pests. The study discusses the problems of ensuring phytosanitary safety of agricultural products and proposes the use of radiation technology instead of chemical treatment. Radiation technology has a long history of research and application, spanning over 75 years. The most extensive and detailed data on the application of this technology have been obtained for gamma installations, which use natural radioactive isotopes. Low-energy (less than 300 keV) electron accelerators were invented relatively recently, so the question of their use in agriculture is relevant. Treatment with low-energy electron radiation combines all the advantages of radiation treatment of food and agricultural products with gamma radiation, and at the same time, significantly reduces the risk of damage to biological structures inside the irradiated object due to the low penetrating power of the radiation. This study notes that low-energy electron accelerators can be successfully used to combat plant infectious diseases, reducing the amount of plant pathogens on seeds, without affecting their growth parameters.

The use of low-energy electron irradiation to prevent microbiological spoilage is also discussed. The nutritional qualities of irradiated products are not significantly altered. The method of radiation disinfestation (control of insect pests) using low-energy electron radiation has also proven to be effective. However, it should be noted that additional research is necessary to determine the optimal doses of low-energy radiation for each type of product and to ensure safety for human health and the environment. Generally, the use of radiation technology in agriculture has great potential and can become an effective means of improving productivity and food safety. This method of food processing has been recognized as safe for human health by several authoritative international organizations, including the UN (FAO), WHO, IAEA, and others.
Keywords: food irradiation, radiosensitivity, microbiological safety, crops, phytosanitary safety, insect-pest, sowing quality of seeds, food quality, shelf life

Conflicts of interest. The authors declared no conflicts of interest.

Article history: Received: 20 March 2023. Accepted: 7 September 2023.

For citation: Tkhorik OV, Kharlamov VA, Polyakova IV, Loy NN, Pomyasova MG, Shishko VI. World experience in the application of low-energy electron irradiation in agriculture. *RUDN Journal of Agronomy and Animal Industries*. 2023; 18(4):541—553. doi: 10.22363/2312-797X-2023-18-3-541-553

Introduction

The main reasons for the loss of agricultural products of plant origin during storage are pathogenic microflora and insect pests. About 50 species of microorganisms are found on seeds, but the number of species is not so significant. The basis of the microflora of cereals is the non-spore-bearing bacillus of the genus *Pseudomonas*, micrococcus, lactic acid fermentation bacteria, and a small number of fungi. During storage, the typical microflora characteristic of benign grain changes significantly. The dominant components of the fungal microflora are *Penicillium* and *Aspergillus* («mould fungi») and other pathogens that cause seed spoilage [1, 2].

Traditionally, in the system of protective measures against phytopathogens of grain, an important place is given to treat seeds and vegetative plants with chemical agents. This method of plant protection mainly leads to the pollution of agricultural products and the environment [3–5]. Radiation technologies are one of the ways to improve the methods of combating plant pathogens.

Radiation technologies in agriculture and food industry have been used for more than 75 years [6–8], mainly for the destruction of insects, suppression of pathogens, increasing shelf life of products, preventing germination of seeds and root crops [9]. According to the IAEA recommendations, for radiation processing of foodstuffs, it is considered safe to use: gamma-irradiation facility with such radionuclides as ^{60}Co or ^{137}Cs; electron irradiation with energy not exceeding 10 MeV; bremsstrahlung with energy no more than 5 MeV [10–12]. Each of these types of radiation has both advantages and disadvantages [13].

The radiation parameters of gamma-irradiation facilities are limited by the characteristics of the radionuclides used in them. Electron accelerators make it possible to change the intensity and energy of the radiation. Therefore, the time of electron irradiation takes several seconds, compared to minutes and even hours, in the case of using gamma radiation sources. In addition, electron accelerators in an inoperative (off) state are safe due to the absence of a radioactive source, which means that they do not require additional physical protection for the service personnel [14, 15].

Electron accelerators are conventionally divided into three groups: low-, medium- and high-energy [15]. The critical feature of electron accelerators is the relatively shallow depth of penetration into the irradiated object. The radiation dose generated in the surface layer of an object depends on the electron energy, the distance to the irradiated object, and the duration of the irradiation. In the case of irradiation of plant seeds with low-energy electrons (with an energy of 70 to 300 keV), the radiation does not reach the embryo and therefore does not violate their growth qualities.

The work aims to assess the possibility of introducing low-energy (up to 300 keV) electron accelerators into the agro-industrial complex.

Design and principle of operation of a low-energy electron accelerator

The initial element of any accelerator is an injector, which contains a source (emitter) of a directed flux of low-energy particles (electrons), as well as high-voltage electrodes and magnets that extract the beam from the source and form it. The basic scheme of the electron acceleration process involves three stages:

(1) beam formation and injection;

(2) beam acceleration;

(3) beam extraction to the target [14].

Many works have been devoted to the design of modern electron accelerators. Accelerators are used for cross-linking of polymers, purification of liquids and gases, surface sterilization, plasma heating during thermonuclear fusion, radiation treatment (disinfection) of food products, and prevention of the germination of agricultural products [15–17].

Depending on their design, accelerators can be classified into linear (i.e. flat cathode) and scanning. The principle of operation of a linear accelerator is based on a typical linear cathode generator. The principle of operation of an electron generator is that when a flat linear tungsten cathode (length from 0.15 to 2 m) is heated, electrons are emitted from this cathode due to thermionic emission. The energy of the emitted electrons depends on the accelerating voltage applied to the cathode. Typically, this voltage varies from 120 to 300 kV. For 70 % of the depth dose, the acceptable range of the processed mass varies from 1 to 380 g/m^2 (300 kV). The upper limits of the above range are 120, 180 and 270 g/m^2 for voltages of 175, 200 and 250 kV, respectively. In modern generators with a wide beam zone, two to four parallel cathodes are installed. These cathodes operate at high voltage, while the anode, which forms the outer shell of the accelerating chamber, is grounded.

The electrons formed in the accelerating chamber are directed to a tungsten target with a thickness of about 12 mm. The target is a foil designed to align the beam and form a rectangular electron field. At the same time, the unit has a cooling system based on nitrogen circulating in it. The cooling system is designed to provide heat dissipation from the constantly heating target.

The accelerator head is housed in a protective casing that completely protects against any radiation. The average annual dose for personnel is about 16.3 mrem, that is, about 10 % of the dose from Earth's natural background radiation. The accelerator head is located directly above the conveyor for faster and more uniform food and agricultural products. The throughput of the accelerator for a dose of 10 kGy depends on the type of machine and ranges from 450 to 1600 cm/min.

Several works [18–21] use a unique rotating grain device, which allows the irradiated samples to rotate, simultaneously shaking and vibrating. This technique was developed specifically for radiation treatment of seeds and cereals. It allows achieving a higher uniformity of irradiation when processing the product with low-energy electrons.

This was experimentally confirmed in [22]. It used indicator beads made of paraffin wax and a radiation-sensitive dye (methyl yellow) to visualize the absorption of electron energy by changing colour (from yellow to red). When the balls were treated with electrons at different accelerating voltages on the rotator tray, the colour of the surface of the balls changed uniformly at all voltages, indicating that the surface of the balls was uniformly exposed to the electron radiation. When the balls were cut, the interior remained yellow, indicating that low energy electrons can only reach a limited (outer) portion of the balls. The penetrating power depends on the energy of the electrons. Electrons with an accelerating voltage of 200 keV penetrated only a few hundred micrometres of the surface. In comparison, electrons with an energy of 1500 keV could penetrate to the centre of the ball. Likewise, the distribution and penetration of electrons have been demonstrated for rice grains coloured with methyl yellow.

The design of the scanning accelerator is described in [23]. Scanning accelerators use a linear tungsten filament as an electron emitter. The essence of this method is that the formed thin beam, with the help of a system of bending magnets, scans the irradiated product. Thereby, due to the time spent by the beam at one point or another in space, the desired dose is accumulated in the product. Works [20–27] were carried out using this method of irradiation.

Radiation surface disinfection of seeds of agricultural plants. E-ventus technology

E-ventus technology is an environmentally friendly method of seed disinfection without chemicals, in which seeds are processed by low energy electrons (less than 300 keV). In Germany, this technology was developed at the Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technologies. E-ventus technology aims to eliminate seed pathogens in the early stages [28, 29].

The principle of operation of the e-ventus installation of EVONTA — Service GmbH [30] is as follows. The installation has two generators of electrons, which are located opposite each other. Passing through the irradiated area, the seeds are exposed to ionizing radiation during the free fall of the grain. At the same time, electrons have sufficiently low energy to penetrate the depths and reach the embryo of seeds [9, 30]. Due to this, the materials are exclusively surface treated. The penetrating power of electron radiation depends on the energy of the particles and the density of the processed product. Thus, for wheat and barley treated with an energy of 145 keV, the penetration depth is 0.066 mm and 0.12 mm, respectively, and for maize with an electron energy of 125 keV — 0.06 mm [28, 29].

The e-ventus method of EVONTA — Service GmbH technology has shown an effective result in the fight against stone smut (*Tilletia caries*) in winter wheat. In the period from 2000 to 2001, the germination of some crops was determined: winter wheat, barley, rye and triticale (a hybrid of wheat and rye). They have been processed with chemicals and e-ventus. It was found that the yield of grain processed by e-ventus technology is the same as that of chemical processing [30].

In 2000, a mobile unit for e-ventus was put into operation. In a stationary installation, electrons with an energy of 105…145 keV, with a capacity of 30 t/h, are used. With an average income of 50 euros per ton of treated seeds, cost recovery is achieved with a production of about 5000…7500 t/year, with large volumes, a profit is generated. The e-ventus seed treatment plants are located in the seed trading centres in Hainichen and Magdeburg (Germany) [9].

The advantages of the e-ventus method, as described on the EVONTA — Service GmbH website [30], are:

- environmentally friendly method;
- faster germination of seeds and better plant vitality;
- lack of resistance of pathogens;
- can be used not only for cereal seeds but also for all types of seed raw materials;
- farm animals do not use chemical fungicides together with the seed.

Radiation disinsection

An industrial-grade electron accelerator manufactured by Nissin High-Voltage Co. Ltd. (Japan) is used to control insect pests. Irradiation at a dose of 3 kGy with electrons with an energy of 80 keV (accelerating voltage 150 kV, current 4.4 and 6.4 mA, at a distance of 5 cm) effectively disinfects brown rice grains previously infected with corn weevil (*Stiophilus zeamais* Motchulsky) and Indian flour moth (*Plodia interpunctella*), as well as adzuki beans infected with weevil [25].

It has been shown that electron irradiation has a different effect on insect pests at different stages of development [20]. Adult specimens of the rust-red flour beetle (*T. castaneum*) and Indian meal moth (*P. interpunctella*), which damage rice, turned out to be more resistant than their larvae and pupae and were inactivated by irradiation at a dose of 4.8 kGy and 7.2 kGy, respectively (electron accelerator Van de Graaff, Nissin High Voltage Engineering Co. Ltd, Japan; accelerating voltage 150 kV, current 4 μA, distance 15 cm, dose rate 0.48 kGy/min, time 1…15 min, electron energy 60 keV). The larvae of the Chinese weevil (*Callosobruchus chinensis* L.) inside the adzuki bean partially survive after electron irradiation [20].

The dose required for disinsection (7.2 kGy; 170 kV, 4 μA, 15 min) is 1/3 of the dose for surface radiation disinfection of rice (21.6 kGy; 170 kV, 4 μA, 45 min) [31].

The radiation sensitivity of the Chinese weevil (*Callosobruchus chinensis* L.), the primary pest of the adzuki bean (*Vigna angularis*), decreased with increasing age. The eggs of the Chinese weevil were highly susceptible to electron radiation, while the 18-day stage (adult insect) was the most resistant. The death of 80 % of adult insects occurs at a dose of 10 kGy (Van de Graaff electron accelerator, Nissin High Voltage Engineering Co. Ltd, Japan; accelerating voltage 170 kV, current 2 μA, time 20 min). Electron irradiation at this dose does not affect the germination of adzuki [27].

The study of brown rice grains by the magnetic resonance method showed that most of the larvae of the corn weevil (*Stiophilus zeamais* Motchulsky) are concentrated on the periphery of the grain and only a few in the centre [26]. Therefore, most of both larvae of insect pests and adults die after electron irradiation at a dose of 30 kGy (Van de Graaff electron accelerator, Nissin HighVoltage Engineering Co. Ltd., Japan, accelerating voltage 170 kV, current 4 μA, distance 15 cm, time 30 min, dose rate 1 kGy/min). In [26], the possibility of an effective combination of electron irradiation and sparing fumigation with phosphine was shown to control insect pests.

Radiation surface disinfection of agricultural products. The quality of irradiated food

Microorganisms are located on the surface of seeds, which means that electrons with low energy (up to 300 keV) can deactivate microorganisms without deteriorating the sowing qualities of seeds [32].

Brown rice, wheat and buckwheat were exposed to electron irradiation (electron accelerator Van de Graaff, Nissin High Voltage Engineering Co. Ltd., Japan) at various modes: 180 kV, 8 μA, 30 min; 200 kV, 14 μA, 15 min; 225 kV, 22 μA, 4 min; 250 kV, 40 μA, 2 min; 300 kV, 40 μA, 2 min; 500 kV, 40 μA, 2 min; at a distance of 17 cm from the irradiated object. The results show that at an accelerating voltage of 180–225 kV, the microbial contamination of the grain decreases to 100 CFU/g. The deterioration in the quality (degradation of starch) of the grain was insignificant [33].

According to [19], the electron energy required to reduce microbial contamination to a level below 10 CFU/g is 60 keV — for brown rice, 75 keV — for wheat, 100 keV — for white pepper, coriander and basil, 130 keV — for buckwheat, 160 keV for unprocessed rice and 210 keV for black pepper. Irradiation with such parameters did not significantly affect the quality of the products (Van de Graaff electron accelerator, Nissin High Voltage Engineering Co. Ltd., Japan; accelerating voltage 180…250 kV, current 8…90 μA, distance 17 cm, time 1…30 min).

Doses of electron irradiation (electron accelerator EBC-150–50–45; accelerating voltage 130 and 150 kV) of wheat and brown rice to reduce microbial contamination to a level of 100 CFU/g were 14 and 12.5 kGy, respectively, and did not cause starch degradation [24].

Lipid oxidation in brown rice was not detected when exposed to low energy electronic radiation (Van de Graaff electron accelerator, Nissin High Voltage Engineering Co. Ltd., Japan; accelerating voltage: 170…200 kV, current 4…14 μA, distance 17 cm, time 60 min). The total microbial number under such irradiation was 10 CFU/g [31].

Electron irradiation up to 200 keV (dose 10 kGy) did not reduce the germination percentage of seeds of adzuki beans and mustard, while in mungo beans, this indicator was reduced [32]. The energy of electrons on the surface of seeds (distance 15 cm from the irradiation source) at an accelerating voltage of 170…200 kV ranges from 60 to 100 keV (Van de Graaff electron accelerator, Nissin High Voltage Engineering Co. Ltd, Japan). The number of seeds studied decreased by less than 10 CFU/g. Similar effects were observed in [34] for seeds of spring wheat cv. Irgin (wide-area electron accelerator Duet, ISE SB RAS, Tomsk, Russia). With an increase in the electron energy to 305 keV, an improvement in the disinfecting effects is observed.

Treatment of spring barley with Vladimir voltage at doses of 30…150 kGy and voltages of 130 and 160 kV (wide-range electron accelerator Duet, Russia) revealed a reduced formation of chlorophylls and carotenes in barley leaves [35]. In the phase of manifestation of tillering, the development of infection of plants with *Bipolaris sorokiniana* is observed with a simultaneous decrease in tillering.

Presowing treatment of seeds of the spring barley cv. Vladimir with low-energy radiation at a voltage amplification of 160 kV and a dose of 4…8 kGy (wide-scale electron accelerator Duet, Russia) with a high degree of susceptibility and disease of seedlings [36].

Presowing treatment with electron radiation with an energy of 100 keV and an absorbed dose of 15 kGy (wide-area electron accelerator Duet, Russia) of spring wheat improves the morphometric parameters of seedlings [37].

While the electron irradiation of 130 keV led to the inhibition of growth rates. Treatment of seeds of cucumber varieties Nezhinskie and Izyashchnye under the same irradiation regimes led to a decrease in the degree of seedling damage by Fusarium [38].

It was found in [39] that the pre-sowing treatment of spring wheat seeds with low-energy radiation (below 300 keV) at doses of 1…8 kGy (wide-angle parametric electron accelerator Duet, Russia) is exposed to reduce the prevalence and severity of the manifestation of *Bipolaris sorokiniana* on seedlings of spring wheat.

To sterilize (kill all microorganisms), soybeans required a dose of 20 kGy of gamma radiation and 26 kGy of electron irradiation (Van de Graaff electron accelerator, Nissin High Voltage Engineering Co. Ltd., Japan) with an energy of 60 keV. Electron irradiation at these doses did not affect the germination of irradiated seeds, while gamma irradiation disrupted growth processes [21]. Unlike gamma irradiation, electronic radiation causes slight lipid oxidation at the surface of the beans.

Disinfection with low-energy (60 keV) electrons (Van de Graaff electron accelerator, Nissin High Voltage Engineering Co. Ltd, Japan; accelerating voltage 170 kV, distance 15 cm, time 3.3–10 min) improves the quality of soybeans for processing them into soy milk and tofu (bean curd). After heat treatment (92 ºC), the preservation (up to 5 days at 35 ºC) of soy milk obtained from irradiated (170 kV, 10 min) soybeans improves [40].

Low-energy electron irradiation is also used to treat seeds to increase their shelf life. In [41], the seeds of pumpkin (*Cucurbita ssp.* L.) and flax (*Linum usitatissimum* L.) were treated with electron radiation with an energy of 200 keV and doses of 8 and 10 kGy (electron accelerator at Bühler AG with auxiliary equipment Laatu, Uswil, Switzerland), as a result of which a decrease in the microbiological load was observed, while the organoleptic properties did not change. The number of volatile aldehydes in the studied seeds increased. In pumpkin seeds after irradiation with a dose of 10 kGy, a decrease in linoleic acid and an increase in oleic acid are observed.

Of course, the problem of contamination of food products of plant origin with bacteria pathogenic for humans is essential. Such infections are often caused by enterohemorrhagic *E. coli* O157: H7, *Salmonella enterica* of various serotypes, *Salmonella enteridis*, *Shigella sonnei* and others. Infections caused by these pathogens can be associated with the consumption of tomatoes, watermelons, unpasteurized orange and apple juices, alfalfa sprouts, clover and beans, and nuts [42].

It has been shown [43] that electron irradiation at a dose of 12 kGy with an efficiency of 80 % disinfects seeds of fenugreek, clover and mung beans artificially seeded with *E. coli* strain K12 (electron accelerator REAMODE, Fraunhofer Institute for Electron Beam and Plasma Technology, Germany; accelerating voltage 140 kV, current 5 μA, distance 100 mm; conveyor speed from 87 mm/s (for a dose of 12 kGy) to 250 mm/s (for a dose of 4 kGy)). This did not affect germination, growth, and the final mass of seedlings of three types of seeds. Irradiation of the bean seeds did not change the seedling morphology, i.e. curl, or seedling colour.

Conclusion

Irradiation with low-energy (up to 300 keV) electron radiation is one of the most effective methods of disinfection (disinfection and disinfestation) of dry food ingredients (except for powdered products) such as cereals, dehydrated vegetables, spices, and legumes with a slight deterioration in their quality. Parts of the grains irradiated with electrons are removed in husks and bran during peeling and grinding; therefore, they do not enter human food. The organoleptic properties and chemical composition of irradiated food products practically do not change.

Irradiation of seeds of agricultural plants (for example, cereals, legumes) with electron radiation with an energy below 300 keV in disinfecting doses does not significantly affect germination, growth, weight, or morphology of seedlings.

Thus, low-energy (up to 300 keV) electron irradiation can be successfully used to combat insects and pathogenic microflora of plants, solve problems of agricultural products' safety, food safety for humans and animals, and solve environmental problems associated with the use of chemical plant protection products.

References/ Библиографический список

1. Muller G, Lietz P, Munch HD. *Mikrobiologiya pishchevykh produktov rastitel'nogo proiskhozhdeniya* [Microbiology of plant foods]. Moscow; 1977. (In Russ.).

Мюллер Г., Литц П., Мюнх Г.Д. Микробиология пищевых продуктов растительного происхождения / пер. с нем. А.М. Калашниковой; под ред. И.М. Грачевой. М.: Пищевая промышленность, 1977. 344 с.

2. Smirnova TA, Kostrova EI. *Mikrobiologiya zerna i produktov ego pererabotki* [Microbiology of grain and products of its processing]. Moscow: Agropromizdat publ.; 1989. (In Russ.).

Смирнова Т.А., Кострова Е.И. Микробиология зерна и продуктов его переработки. М.: Агропромиздат, 1989. 159 с.

3. Pinstrup-Anderson P, Pandy-Lorch R, Rosegrant MW. *The world food situation: recent developments, emerging issues, and long-term prospects*. Vision 2020: Food Policy Report. Washington, DC: International Food Policy Research Institute; 1997.

4. Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, et al. Forecasting agriculturally driven global environmental change. *Science*. 2001;292(5515):281–284. doi: 10.1126/science.1057544

5. Makarova MA, Shevtsova AA. Prospects of application of new means of protection against diseases in maize seed crops. *Far East agrarian herald*. 2017;(3):55–60. (In Russ.).

Макарова М.А., Шевцова А.А. Перспективы применения новых средств защиты от болезней в семенных посевах кукурузы // Дальневосточный аграрный вестник. 2017. Т. 43. № 3. С. 55–60.

6. Morrison RM. *An economic analysis of electron accelerators and cobalt-60 for irradiating food.* Technical Bulletin No. 1762. Washington, DC; 1989.

7. Pikaev AK. Current state of radiation processing. *Russian Chemical Reviews*. 1995;64(6):609–640. (In Russ.).

Пикаев А.К. Современное состояние радиационной технологии // Успехи химии. 1995. Т. 64. № 6. С. 609–640.

8. Chernyaev AP, Varzar SM. Particle accelerators in modern world. *Yadernaya fizika*. 2014;77(10):1266–1278. (In Russ.). doi: 10.7868/S0044002714100031

Черняев А.П., Варзарь С.М. Ускорители в современном мире // Ядерная физика. 2014. Т. 77. № 10. С. 1266–1278. doi: 10.7868/S0044002714100031

9. Kozmin GV, Geraskin SA, Sanzharova NI. *Radiatsionnyye tekhnologii v sel'skom khozyaystve i pishchevoy promyshlennosti* [Radiation technologies in agriculture and food industry]. Obninsk; 2015. (In Russ.).

Козьмин Г.В., Гераськин С.А., Санжарова Н.И. Радиационные технологии в сельском хозяйстве и пищевой промышленности. Обнинск: ВНИИРАЭ, 2015. 400 с.

10. Bezuglov VV, Bryazgin AA, Vlasov AY, Voronin LA, Panfilov AD, Radchenko VM, et al. Industrial electron accelerators ILU for medical products sterilization and food treatment. *Physics of elementary particles and atomic nuclei, letters*. 2016;13(7):1581–1585. (In Russ.).

Безуглов В.В., Брязгин А.А., Власов А.Ю., Воронин Л.А., Панфилов А.Д., Радченко В.М., Ткаченко В.О., Штарклев Е.А. Промышленные ускорители электронов ИЛУ для стерилизации медицинских изделий и обработки пищевых продуктов // Письма в ЭЧАЯ. 2016. Т. 13. № 7. С. 1581–1585.

11. Bryazgin AA, Bezuglov VV, Voronin LA, Korobeynikov MV, Maximov SA, Nekhaev VE, et al. Industrial electron accelerators type ILU for food products treatment. In: *Radiation technologies in agriculture and food industry: Current state and prospects: conference proceedings*. Obninsk; 2018. p.127–131. (In Russ.).

Брязгин А.А., Безуглов В.В., Воронин Л.А., Коробейников М.В., Максимов С.А., Нехаев В.Е., Радченко В.М., Сидоров А.В., Ткаченко В.О., Факторович Б.Л. Промышленные ускорители ИЛУ для облучения пищевых продуктов // Радиационные технологии в сельском хозяйстве и пищевой промышленности: состояние и перспективы: сб. докл. межд. науч.-практ. конф., Обнинск, 26–28 сентября 2018 г. Обнинск: ФГБНУ ВНИИРАЭ, 2018. С. 127–131.

12. Sanzharova NI, Kozmin GV, Bondarenko VS. Nuclear technologies in agriculture: Science and technology development strategy. *Innovatics and Expert Examination*. 2016;(1):197–206. (In Russ.).

Санжарова Н.И., Козьмин Г.В., Бондаренко В.С. Радиационные технологии в сельском хозяйстве: стратегия научно-технического развития // Инноватика и экспертиза. 2016. Т. 16, № 1. С. 197–206.

13. Pimemov EP, Pavlov AN, Vasileva NA, Morozova AI. The effects of different regimes of a pulsed linear electron accelerator on the microorganisms that contaminate spices. In: *Radiation technologies in agriculture and food industry: Current state and prospects: conference proceedings*. Obninsk; 2018, p.100–103. (In Russ.).

Пименов Е.П., Павлов А.Н., Васильева Н.А., Морозова А.И. Действие разных режимов импульсного линейного ускорителя электронов на микроорганизмы, обсеменяющие специи // Радиационные технологии в сельском хозяйстве и пищевой промышленности: состояние и перспективы: сб. докл. межд. науч.-практ. конф., Обнинск, 26–28 сентября 2018 г. Обнинск: ФГБНУ ВНИИРАЭ, 2018 г. С. 100–103.

14. Zabayev VN. *Primenenie uskoritelei v nauke i promyshlennosti* [Application of accelerators in science and industry]. Tomsk; 2008. (In Russ.).

Забаев В.Н. Применение ускорителей в науке и промышленности. Томск: Изд-во ТПУ, 2008. 195 с.

15. Chernyaev AP. *Uskoriteli v sovremennom mire* [Accelerators in the world today]. Moscow; 2012. (In Russ.).

Черняев А.П. Ускорители в современном мире. М.: Изд-во МГУ, 2012. 368 с.

16. Alimov AS. *Prakticheskoe primenenie elektronnykh uskoriteley* [Practical applications of electronic accelerators]. Preprint MSU SINP № 2011–13/877. (In Russ.).

Алимов А.С. Практическое применение электронных ускорителей // Препринт НИИЯФ МГУ. 2011. Т. 13. № 877. С. 1–40.

17. Scharf W, Wieszczycka W. Particle accelerators for industrial processing (Part 1). *Maintenance and Reliability*. 2001;(2–3):10–25.

18. Hayashi T. Decontamination of dry food ingredients and seeds with «soft-electrons» (low-energy electrons). *Food Sci Technol Int Tokyo.* 1998;4(2):114–120. doi: 10.3136/fsti9596t9798.4.114

19. Hayashi T, Takahashi Y, Todoriki S. Sterilization of foods with low-energy electrons («soft-electrons»). *Radiat Phys Chem*. 1998;52(1–6):73–76. doi: 10.3136/fsti9596t9798.4.114

20. Imamura T, Todoriki S, Sota N, Nakakita H, Ikenaga H, Hayashi T. Effect of ‘‘soft-electron’’ (low-energy electron) treatment on three stored-product insect pests. *J Stored Prod Res.* 2004;40(2):169–177. doi: 10.1016/S0022-474X(02)00095-4

21. Kikuchi OK, Todoriki S, Saito M, Hayashi T. Efficacy of soft-electron (low-energy electron beam) for soybean decontamination in comparison with gamma-rays. *J Food Sci.* 2003;68(2):649–652. doi: 10.1111/j.1365-2621.2003.tb05725.x

22. Hayashi T, Todoriki S. Low energy electron irradiation of food for microbial control. In: *Irradiation for Food Safety and Quality*. Vienna; 2001. p.118–128.

23. Mehnert R, Klenert P, Prager L. Low-energy electron accelerators for industrial radiation processing. *Radiat Phys Chem*. 1993;42(1–3):525–529. doi: 10.1016/0969-806X(93)90302-B

24. Baba T, Kaneko H, Taniguchi S. Soft electron processor for surface sterilization of food material. *Radiat Phys Chem*. 2004;71(1–2):209–211. doi: 10.1016/j.radphyschem.2004.03.079

25. Imamura T, Miyanoshita A, Todoriki S, Hayashi T. Usability of a soft-electron (low-energy electron) machine for disinfestation of grains contaminated with insect pests. *Radiat Phys Chem*. 2004;71(1–2):213–215. doi: 10.1016/j.radphyschem.2004.03.080

26. Imamura T, Todoriki S, Miyanoshita A, Horigane AK, Yoshida M, Hayashi T. Efficacy of soft-electron (low-energy electron) treatment for disinfestation of brown rice containing different ages of the maize weevil, Sitophilus zeamais Motschulsky. *Radiat Phys Chem*. 2009;78(7–8):627–630. doi: 10.1016/j.radphyschem.2009.03.058

27. Rami Reddy PV, Todoriki S, Miyanoshita A, Imamura T, Hayashi T. Effect of soft electron treatment on adzuki bean weevil, *Callosobruchus chinensis* (L.) (Col., Bruchidae). *J Appl Entomol*. 2006;130(6–7):393–399.

28. Cutrubinis M, Delincee H, Stahl M, Roder O, Schaller HJ. Erste ergebnisse zum nachweis einerelektronenbehandlung von mais zur beizung bzw. entkeimung und entwesung. *Gesunde Pflanzen*. 2005;57(5):129–136. doi: 10.1007/s10343-005-0074-y

29. Cutrubinis M, Delincee H, Stahl M, Roder O, Schaller HJ. Detection methods for cereal grains treated with low and high energy electrons. *Radiat Phys Chem.* 2005;72(5):639–644. doi: 10.1016/j.radphyschem.2004.03.089

30. EVONTA — Service Gmb H. Available at: www.evonta.de (Accessed 07.11.2019).

31. Hayashi T, Okadome H, Toyoshima H, Todoriki S, Ohtsubo K. Rheological properties and lipid oxidation of rice decontaminated with low-energy electrons. *J. Food Prot*. 1998;61(1):73–77. doi: 10.4315/0362-028X-61.1.73

32. Todoriki S, Hayashi T. Disinfection of seeds and sprout inhibition of potatoes with low energy electrons. *Radiat Phys Chem*. 2000;57(3–6):253–255. doi: 10.1016/S0969-806X(99)00389-8

33. Hayashi T, Takahashi Y, Todoriki S. Low-energy electron effects on the sterility and viscosity of grains. *J Food Sci.* 2006;62(4):858–860. doi: 10.1111/j.1365-2621.1997.tb15472.x

34. Isemberlinova AA, Poloskov AV, Egorov IS, Kurilova AA, Nuzhnyh SA, Remnev GE. Influence of a pulsed electron beam on the sowing quality of wheat. *Key Eng Mater*. 2018;769:172–180. doi: 10.4028/www.scientific.net/KEM.769.172

35. Loy NN, Sanzharova NI, Gulina SN, Suslova OV, Chizh TV, Vorobyov MS, et al. Evaluation of the effect of pre-sowing electron irradiation of barley seeds on plant development and disease incidence. *J Phys Conf Ser*. 2021;2064012101. doi: 10.1088/1742-6596/2064/1/012101

36. Loy NN, Sanzharova NI, Gulina SN, Vorobiyov MS, Koval NN, Doroshkevich SY, et al. Influence of electronic irradiation on the affection of barley by root rot. *J Phys Conf Ser*. 2019;1393012107.

37. Doroshkevich SY, Artyomov KP, Tereshchenko NN, Zyubanova TI, Vorobyov MS, Akimova EE, et al. Presowing treatment of spring wheat seeds by a pulsed electron beam in the atmosphere. *High Energy Chemistry*. 2021;55(4):326–332. (In Russ.). doi: 10.31857/S0023119321040069

Дорошкевич С.Ю., Артёмов К.П., Терещенко Н.Н., Зюбанова Т.И., Воробьёв М.С., Акимова Е.Е., Минаева О.М., Покровская Е.А., Шин В.И., Торба М.С., Леванисов В.А. Предпосевная обработка семян яровой пшеницы импульсным электронным пучком в атмосфере // Химия высоких энергий. 2021. Т. 55. № 4. С. 326–332. doi: 10.31857/S0023119321040069

38. Loy NN, Sanzharova NI, Gulina SN, Suslova OV. Influence of electronic radiation on radio resistance of phytopathogenic microflora of cucumber. *Rossiiskaia selskokhoziaistvennaia nauka*. 2021;(4):47–50. (In Russ.). doi: 10.31857/S2500262721040104

Лой Н.Н., Санжарова Н.И., Гулина С.Н., Суслова О.В. Влияние электронного излучения на радиорезистентность фитопатогенной микрофлоры огурца // Российская сельскохозяйственная наука. 2021. № 4. С. 47–50. doi: 10.31857/S2500262721040104

39. Loy NN, Sanzharova NI, Gulina SN, Vorobev MS. Influence of electronic radiation of seeds of grain crops on their resistance to damage of root rot. In: Nuclear and physical technologies in agriculture and food industry: conference proceedings. 2020. p.346–350. (In Russ.).

Лой Н.Н., Санжарова Н.И., Суслова О.В., Гулина С.Н., Воробьев М.С. Влияние электронного облучения семян зерновых культур на их устойчивость к поражению корневой гнилью // Ядерно-физические исследования и технологии в сельском хозяйстве (к 50-летию со дня образования ФГБНУ ВНИИ радиологии и агроэкологии): сборник докладов междунар. науч.-практ. конф. Обнинск, 2020. С. 346–350.

40. Todoriki S, Kikuchi OK, Nakaoka M, Miike M, Hayashi T. Soft electron (low energy electron) processing of foods for microbial control. *Radiat Phys Chem*. 2002;63(3–6):349–351. doi: 10.1016/S0969-806X(01)00588-6

41. Aisala H, Nygren H, Seppänen-Laakso T, Heiniö RL, Kießling M, Aganovic K, et al. Comparison of low energy and high energy electron beam treatments on sensory and chemical properties of seeds. *Int Food Res J*. 2021;148:110575. doi: 10.1016/j.foodres.2021.110575

42. Markova YA, Alekseenko AL, Kramarskiy AV, Savilov ED. Plants as an element of environmental chain circulation of pathogenic for human bacteria. *Siberian Medical Journal (Irkutsk)*. 2012;114(7):11–14. (In Russ.).

Маркова Ю.А., Алексеенко А.Л., Крамарский А.В., Савилов Е.Д. Растения как одно из звеньев цепи циркуляции патогенных для человека бактерий в окружающей среде // Сибирский медицинский журнал. 2012. Т. 114. № 7. С. 11–14.

43. Fan X, Sokorai K, Weidauer A, Gotzmann G, Rogner FH, Koch E. Comparison of gamma and electron beam irradiation in reducing populations of *E. coli* artificially inoculated on mung bean, clover and fenugreek seeds, and affecting germination and growth of seeds. *Radiat Phys Chem*. 2017;130:306–315. doi: 10.1016/j.radphyschem.2016.09.015

About authors:

Tkhorik Oksana Vladimirovna — Researcher, Russian Institute of Radiology and Agroecology of National Research Centre «Kurchatov Institute», 1/1 Kievskoe shosse, Obninsk, Kaluga region, 249035, Russian Federation; e-mail: oxana.tkhorik@gmail.com
ORCID: 0000-0001-5213-2150

Kharlamov Vladimir Aleksandrovich — Candidate of Biological Sciences, Senior Researcher, Russian Institute of Radiology and Agroecology of National Research Centre «Kurchatov Institute», 1/1 Kievskoe shosse, Obninsk, Kaluga region, 249035, Russian Federation; e-mail: kharlamof@gmail.com
ORCID: 0000-0003-3479-1800

Polyakova Irina Vladimirovna — Researcher, Russian Institute of Radiology and Agroecology of National Research Centre «Kurchatov Institute», 1/1 Kievskoe shosse, Obninsk, Kaluga region, 249035, Russian Federation; e-mail: irinaamchenkina@mail.ru
ORCID: 0000-0003-1602-7921

Loy Nadezhda Nikolaevna — Candidate of Biological Sciences, Leading Researcher, Russian Institute of Radiology and Agroecology of National Research Centre «Kurchatov Institute», 1/1 Kievskoe shosse, Obninsk, Kaluga region, 249035, Russian Federation; e-mail: loy.nad@yandex.ru
ORCID: 0000-0001-9984-0883

Pomyasova Maria Gennadievna — Researcher, Russian Institute of Radiology and Agroecology of National Research Centre «Kurchatov Institute», 1/1 Kievskoe shosse, Obninsk, Kaluga region, 249035, Russian Federation; e-mail: mariya-zelenetskaya@mail.ru
ORCID: 0000-0003-3922-1567

Shishko Valentin Igorevich — Researcher, Russian Institute of Radiology and Agroecology of National Research Centre «Kurchatov Institute», 1/1 Kievskoe shosse, Obninsk, Kaluga region, 249035, Russian Federation; e-mail: valentine585@yandex.ru
ORCID: 0000-0002-0526-0579

Мировой опыт применения облучения низкоэнергетическими электронами в сельском хозяйстве

О.В. Тхорик, В.А. Харламов ✉, И.В. Полякова, Н.Н. Лой, М.Г. Помясова, В.И. Шишко

Всероссийский научно-исследовательский институт радиологии и агроэкологии Национального исследовательского центра «Курчатовский институт», *г. Обнинск, Российская Федерация*
✉ kharlamof@gmail.com

Аннотация. По данным многолетних наблюдений ФАО, потери сельхозпродукции растительного происхождения оценивают от 10 до 30 %. Основными причинами этих потерь являются фитопатогены, микроорганизмы порчи и насекомые-вредители. Рассматриваются проблемы обеспечения фитосанитарной безопасности сельскохозяйственной продукции и предлагается использование радиационной технологии вместо обработки химическими реагентами. Радиационные технологии имеют давнюю историю изучения и применения, длящуюся уже более 75 лет. Наиболее масштабные и подробные данные применения технологии получены для гамма-установок, в которых используются естественные радиоактивные изотопы. Ускорители электронов с низкой энергией (ниже 300 кэВ) изобрели относительно недавно, поэтому вопрос их применения в сельском хозяйстве актуален. Обработка низкоэнергетическим электронным излучением сочетает в себе все преимущества радиационной обработки пищевых и сельскохозяйственных продуктов гамма-излучением, и в то же время, за счет малой проникающей способности излучения, значимо снижает риск повреждения биологических структур во внутреннем объеме облучаемого объекта. В данной работе отмечено, что низкоэнергетические ускорители электронов могут быть успешно использованы для борьбы с инфекционными болезнями растений, снижая количество фитопатогенов на семенах. При этом нарушение ростовых параметров семян не наблюдается. Также рассмотрено использование облучения низкоэнергетическими электронами для предотвращения микробиологической порчи. Пищевые качества облученных продуктов существенно не меняются. Метод радиационной дезинсекции (борьбы с насекомыми-вредителями) низкоэнергетическим электронным излучением также показал свою эффективность. Однако, стоит отметить, что необходимы дополнительные исследования, чтобы определить оптимальные дозы облучения низкоэнергетическим излучением для каждого вида продукции и обеспечить безопасность для здоровья человека и окружающей среды. В целом, использование радиационной технологии в сельском хозяйстве имеет большой потенциал и может стать эффективным способом повышения производительности и безопасности пищевых продуктов. Данный метод обработки продуктов питания признан безопасным для здоровья человека рядом авторитетных международных организаций: ООН (ФАО), ВОЗ, МАГАТЭ и др.

Ключевые слова: облучение пищевых продуктов, радиочувствительность, микробиологическая безопасность, сельскохозяйственные культуры, фитосанитарная безопасность, насекомые-вредители, посевные качества семян, качество пищевых продуктов, срок годности

Заявление о конфликте интересов. Автор заявляет об отсутствии конфликта интересов.

История статьи: поступила в редакцию 20 марта 2023 г., принята к публикации 7 сентября 2023 г.

Для цитирования: *Tkhorik O.V., Kharlamov V.A., Polyakova I.V., Loy N.N., Pomyasova M.G., Shishko V.I.* World experience in the application of low-energy electron irradiation in agriculture // Вестник Российского университета дружбы народов. Серия: Агрономия и животноводство. 2023. Т. 18. № 4. С. 541—553. doi: 10.22363/2312-797X-2023-18-3-541-553

Об авторах:

Тхорик Оксана Владимировна — научный сотрудник, Всероссийский научно-исследовательский институт радиологии и агроэкологии Национального исследовательского центра «Курчатовский институт», Российская Федерация, 249035, Калужская область, г.о. Обнинск, г. Обнинск, Киевское шоссе, д. 1, к. 1; e-mail: oxana.tkhorik@gmail.com
ORCID: 0000-0001-5213-2150

Харламов Владимир Александрович — кандидат биологических наук, старший научный сотрудник, Всероссийский научно-исследовательский институт радиологии и агроэкологии Национального исследовательского центра «Курчатовский институт», Российская Федерация, 249035, Калужская область, г. о. Обнинск, г. Обнинск, Киевское шоссе, д. 1, к. 1; e-mail: kharlamof@gmail.com
ORCID: 0000-0003-3479-1800

Полякова Ирина Владимировна — научный сотрудник, Всероссийский научно-исследовательский институт радиологии и агроэкологии Национального исследовательского центра «Курчатовский институт», Российская Федерация, 249035, Калужская область, г.о. Обнинск, г. Обнинск, Киевское шоссе, д. 1, к. 1; e-mail: irinaamchenkina@mail.ru
ORCID: 0000-0003-1602-7921

Лой Надежда Николаевна — кандидат биологических наук, ведущий научный сотрудник, Всероссийский научно-исследовательский институт радиологии и агроэкологии Национального исследовательского центра «Курчатовский институт», Российская Федерация, 249035, Калужская область, г.о. Обнинск, г. Обнинск, Киевское шоссе, д. 1, к. 1; e-mail: loy.nad@yandex.ru
ORCID: 0000-0001-9984-0883

Помясова Мария Геннадьевна — научный сотрудник, Всероссийский научно-исследовательский институт радиологии и агроэкологии Национального исследовательского центра «Курчатовский институт», Российская Федерация, 249035, Калужская область, г.о. Обнинск, г. Обнинск, Киевское шоссе, д. 1, к. 1; e-mail: mariya-zelenetskaya@mail.ru
ORCID: 0000-0003-3922-1567

Шишко Валентин Игоревич — научный сотрудник, Всероссийский научно-исследовательский институт радиологии и агроэкологии Национального исследовательского центра «Курчатовский институт», Российская Федерация, 249035, Калужская область, г.о. Обнинск, г. Обнинск, Киевское шоссе, д. 1, к. 1; e-mail: valentine585@yandex.ru
ORCID: 0000-0002-0526-0579