

Article

Improving Grain Safety Using Radiation Dose Technologies

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Abstract

Reducing post-harvest losses of cereal crops is a key challenge for ensuring global food security amid the limited arable land and growing population. This study investigates the effectiveness of electron beam irradiation (5 MeV, ILU-10 accelerator) as a physical decontamination method for various cereal crops cultivated in Kazakhstan. Samples were irradiated at doses ranging from 1 to 5 kGy, and microbiological indicators—including Quantity of Mesophilic Aerobic and Facultative Anaerobic Microorganisms (QMAFAnM), yeasts, and molds—were quantified according to national standards. Experimental results demonstrated an exponential decline in microbial contamination, with a >99% reduction achieved at doses of 4–5 kGy. The modeled inactivation kinetics showed strong agreement with the experimental data: $R^2 = 0.995$ for QMAFAnM and $R^2 = 0.948$ for mold, confirming the reliability of the exponential decay models. Additionally, key quality parameters—including protein content, moisture, and gluten—were evaluated post-irradiation. The results showed that protein levels remained largely stable across all doses, while slight but statistically insignificant fluctuations were observed in moisture and gluten contents. Principal component analysis and scatterplot matrix visualization confirmed clustering patterns related to radiation dose and crop type. The findings substantiate the feasibility of electron beam treatment as a scalable and safe technology for improving the microbiological quality and storage stability of cereal crops.

Keywords: grain crops; shelf life; spoilage microorganisms; food irradiation; food safety



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1. Introduction

Post-harvest losses represent a major challenge to global food security, with the Food and Agriculture Organization estimating that approximately one-third (1.3 billion tons) of all food produced is lost annually due to factors such as pest infestation, microbial spoilage, and inadequate storage practices [1]. In cereal grains, these losses are particularly pronounced during post-harvest handling and storage, exacerbating nutritional insecurity and

economic losses, especially in developing economies. Sustainable preservation methods are urgently needed to reduce food waste, preserve nutritional quality, and minimize chemical inputs [2,3]. These losses not only reduce the availability of food but also impact sustainability efforts by wasting agricultural inputs such as water, labor, and energy. According to the World Bank, post-harvest grain losses can range from 10% to 30% in sub-Saharan Africa and Asia, depending on the crop type and storage conditions [4].

Traditional preservation methods, including chemical fumigation and synthetic pesticides, raise concerns regarding human health, environmental contamination, and the development of resistant strains of pests and fungi. As a result, there is growing interest in alternative, non-chemical preservation technologies that can ensure food safety while supporting environmentally sustainable practices [5].

Ionizing radiation has emerged as a promising method for post-harvest treatment. Techniques such as gamma rays, X-rays, and electron beam irradiation can effectively reduce microbial contamination, suppress sprouting, and extend the shelf life of agricultural commodities without leaving chemical residues [6]. This approach is recognized by international agencies such as the Codex Alimentarius Commission, the International Atomic Energy Agency (IAEA), and the World Health Organization (WHO) [7,8].

Recent studies have demonstrated that irradiation can effectively reduce fungal contamination and microbial loads in stored grains, contributing to food safety and improved storage outcomes. Electron beam (e-beam) irradiation has advantages such as precise dose control, short processing time, and scalability for industrial applications. Recent studies have shown that e-beam doses in the range of 2–5 kGy can significantly reduce levels of molds, yeasts, and mesophilic bacteria in various cereal grains while maintaining their nutritional and sensory quality [9,10]. Previous studies conducted in Kazakhstan have demonstrated the relevance of non-chemical disinfection technologies, such as ultraviolet and radiation treatments, in enhancing the microbiological safety of grain and animal products [11,12].

Moreover, radiation technology is closely aligned with the principles of sustainable agriculture by reducing dependence on synthetic chemical treatments, such as pesticides and fungicides, which are associated with environmental contamination and risks to human health. The application of ionizing radiation for microbial decontamination eliminates the need for chemical residues in food products and minimizes post-treatment waste. Unlike conventional pesticides, which may contribute to soil and water pollution, radiation does not leave persistent environmental by-products, thereby supporting ecologically responsible food processing systems [13,14].

For instance, Aziz et al. demonstrated that low-dose γ -irradiation is highly effective in eliminating pathogenic microorganisms in cereal grains while maintaining their nutritional integrity [15]. Specifically, doses up to 5 kGy were sufficient to achieve microbial decontamination without significant losses in key nutrient components such as proteins and vitamins. Similarly, Köksel et al. reported the improved storability and microbial safety of durum wheat and its derived products (e.g., spaghetti) when exposed to gamma irradiation doses up to 1 kGy. However, they noted that doses above this threshold may negatively affect the milling properties and technological quality of the grain [16].

Despite these promising findings, much of the available research has been conducted at the regional level and lacks integration into globally validated safety frameworks or harmonized dose–response models. Studies by Mitra et al. and Sirohi et al. have not only highlighted the efficacy of ionizing radiation for pest and microbial control, but also its environmental benefits, including reductions in pesticide use and chemical residues [17,18]. Nevertheless, few studies have systematically benchmarked irradiation outcomes—particularly

electron beam technologies—against international safety standards such as those set by Codex Alimentarius or the IAEA.

Cereal grains, such as wheat, barley, and oats, represent staple food sources worldwide due to their high content of carbohydrates, proteins, dietary fiber, and bioactive compounds. However, in addition to microbiological safety, the technological and nutritional quality of cereals—measured through parameters such as protein content, moisture, and gluten strength—are critical for their processing, consumer acceptance, and end-use applications. These parameters determine dough rheology, baking performance, and the storage stability of cereal-based products [19].

Radiation technologies, particularly electron beam irradiation, have been widely studied for their efficacy in reducing microbial contamination and extending the shelf life of cereal grains. Yet, concerns persist about the possible impact of ionizing radiation on functional and nutritional attributes. Several studies have shown that protein content remains largely stable at doses up to 5 kGy, with no significant denaturation or degradation observed [20]. Similarly, moisture content tends to be unaffected, provided the irradiation is performed under controlled ambient conditions, avoiding radiolytic water loss [21]. However, excessive doses of ionizing radiation can negatively impact cereal quality parameters such as gluten functionality and milling performance. For example, Rigas et al., 2023, reported that high-dose gamma irradiation adversely affected wheat's processing traits and technological quality [22]. Köksel et al. observed minor reductions in the gluten index of durum wheat after γ -irradiation at doses above 3 kGy, though the pasta-making quality remained within acceptable limits [16].

Therefore, when implementing radiation-based microbial control strategies in cereals, it is crucial to balance microbial safety with the preservation of key technological traits. Comprehensive evaluations that incorporate both microbiological and physicochemical assessments are needed to establish safe, effective dose ranges that align with international food safety standards and consumer expectations.

Limited research has explored the effects of electron beam irradiation on cereal grains commonly cultivated in Kazakhstan. Previous studies have largely focused on gamma irradiation or generalized systems, leaving a gap in the understanding of real-world grain varieties under region-specific conditions. This study addresses that gap by evaluating the microbiological and physicochemical responses of wheat, barley, and oats to electron beam doses between 2 and 5 kGy, in line with food safety. Therefore, the aim of this study is to evaluate the effectiveness of electron beam irradiation (2–5 kGy) as a non-chemical method for improving the microbiological safety and storage stability of cereal grains cultivated in Kazakhstan.

2. Materials and Methods

2.1. Research Organization

The selected cereal varieties—wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and oat (*Avena sativa*)—represent the most widely cultivated and economically significant grain crops in Kazakhstan. Each species exhibits distinct morphological features such as husk thickness, grain texture, and surface area, which play critical roles in microbial colonization and influence their susceptibility to irradiation-based decontamination.

The list of analyzed grain crop samples, including varietal names, physical characteristics, and sample sizes, is provided in Table 1.

Table 1. List of analyzed cereal grain samples with varietal names and physical characteristics.

Item #	Sample Name	Number of Samples, pcs.	Average Weight of Samples, g	Dimensions of Samples (L × W × H), mm
1	Wheat (Winter, Sapaly)	12	55	110 × 75 × 10
2	Wheat (Farabi 1)	12	60	110 × 75 × 10
3	Wheat (Winter, soft, Mereke 70)	12	60	110 × 75 × 13
4	Triticale (Elite Kozha, Harvest 2024)	12	60	110 × 75 × 13
5	Wheat (3rd grade)	12	65	110 × 75 × 15
6	Wheat (Glassy 24)	12	50	110 × 75 × 12
7	Wheat (Egemen 20, 1 reproduction, autumn)	12	40	110 × 75 × 10
8	Wheat (Kazakhstan 10, 1 reproduction autumn/summer)	12	35	110 × 75 × 10
9	Wheat (Glassy 24, elite, autumn)	12	25	110 × 75 × 9
10	Wheat (Winter, Kazakhstan)	12	60	110 × 75 × 15
11	Wheat (Forage)	12	60	110 × 75 × 15
12	Barley	12	65	110 × 75 × 15
13	Oats	12	35	110 × 75 × 10

Samples were randomly assigned to two treatment groups ($n = 3$ per dose level):

1. Control group: Non-irradiated samples that were transported and stored under the same environmental conditions as the treated samples (2 samples per cereal type);
2. Irradiated group: Samples exposed to electron beam treatment with the ILU-10 accelerator, with absorbed doses of 1, 2, 3, 4, and 5 kGy (2 samples of each cereal variety were prepared for one dose of radiation).

The overall experiment was repeated 3 times for each dose.

All samples were stored and irradiated under standardized environmental conditions: a temperature of 20 °C and relative humidity of 55% [23,24]. These parameters were maintained consistently for both control and irradiated groups to eliminate potential bias caused by external variables.

2.2. Irradiation Procedure

Electron beam irradiation was performed using the ILU-10 industrial accelerator (Budker Institute of Nuclear Physics, Novosibirsk, Russia). Grain samples were packed in hermetically sealed polyethylene Zip-Lock bags to prevent moisture exchange and contamination. The packaged samples were placed on specialized scissor-type lifting tables mounted on an automated roller conveyor system. The conveyor transported the samples through the irradiation zone at a constant speed of 4 cm/s, with the grains positioned horizontally on one side to ensure uniform exposure.

The absorbed radiation dose was controlled by adjusting the average beam current (I_{av}) of the accelerated electrons while maintaining a constant conveyor speed. An example of sample packaging and placement during irradiation is shown in Figure 1, and a schematic representation of the irradiation setup is presented in Figure 2. The detailed parameters of the electron beam irradiation process, including beam energy, current, frequency, conveyor speed, and absorbed dose, are summarized in Table 2.

Dosimetric control during the irradiation of grain samples with accelerated electrons was performed in accordance with the international standard ISO/ASTM 51900:2023 [25]. The absorbed radiation dose was measured using GEX B3 radiochromic film dosimeters (GEX Corporation, Centennial, CO, USA), which were placed on the upper and lower surfaces of the grain samples, as well as within the bulk of the samples, using a model matrix to simulate internal conditions. This arrangement ensured the accurate monitor-

ing of the spatial dose distribution and verification of the target dose delivery for each irradiation mode.



Figure 1. Packaging and arrangement of cereal grain samples for irradiation using the ILU-10 electron beam accelerator.

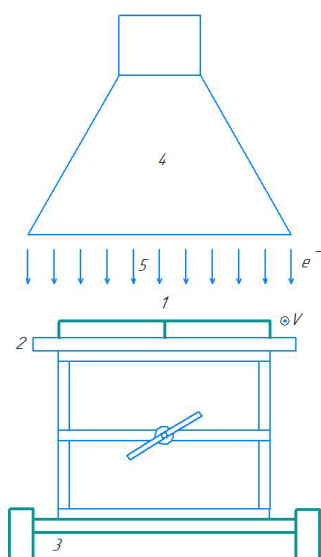


Figure 2. Schematic diagram of the electron beam irradiation setup for cereal grain samples with the ILU-10 accelerator. 1—packed samples; 2—scissor-type lifting tables; 3—automated roller conveyor; 4—electron beam discharge device of the ILU-10 accelerator; 5—direction of accelerated electron beam; V—direction of sample movement.

Table 2. Parameters of the irradiation of cereal crop samples using the ILU-10 accelerator.

Mode #	E, MeV	I_{imp} , mA	f, Hz	I_{av} , mA	Conveyor Speed, cm/s	Irradiation	D, kGy
1	5	122	4	0.24	4	On the one side	1
2	5	122	8	0.49	4	On the one side	2
3	5	122	12	0.73	4	On the one side	3
4	5	122	16	0.98	4	On the one side	4
5	5	122	20	1.22	4	On the one side	5

E—energy of accelerated electrons; I_{imp} —pulse current; f—pulse repetition frequency; I_{av} —average beam current; D—absorbed radiation dose; irradiation was conducted on one side of the horizontally oriented sample surface.

2.3. Microbiological Methods

A peptone salt solution (PSS) was prepared by dissolving 1 g of PEPTON-R and 8.5 g of NaCl in a 1000 mL volumetric flask. The volume was brought to the mark with distilled water, and the solution was sterilized in an autoclave at 1.1 atm pressure for 20 min.

For the determination of yeast and mold counts for each sample, 10 g of grain was placed in 100 mL sterile flasks, followed by the addition of 90 mL of sterilized PSS. Aliquots were inoculated onto Sabouraud dextrose agar (GM063-500G, HiMedia Laboratories Limited, India) in Petri dishes. Plates were incubated under aerobic conditions at a temperature of 25 ± 1 °C for 5 days. A preliminary count of colonies was performed on day 3, followed by a final enumeration on day 5.

For the enumeration of QMAFAnM, 10 g of grain was suspended in 90 mL of PSS. Serial dilutions (10^2 and 10^3) were prepared and plated onto nutrient agar (M001-500G, HiMedia Laboratories Limited, Mumbai, India). Plates were incubated aerobically at 35 ± 1 °C for 24 ± 3 h. Colony-forming units (CFUs) were counted on Petri dishes containing 15 to 300 colonies, ensuring the accurate statistical representation of microbial populations.

The results are given in CFU/g, where CFUs (colony-forming units) are the number of viable microorganisms contained in 1 g of sample, capable of forming the separate colony on the nutrient medium.

All microbiological studies of each grain sample were carried out 3 times, and average values were given.

2.4. Assessment of Cereal Grain Quality Parameters

The physicochemical quality of cereal grains was evaluated using a near-infrared (NIR) spectroscopy analyzer Infralyum FT-12 (Lumex Instruments, St. Petersburg, Russia). The following parameters were determined in intact grain samples: moisture content (%), protein content (% on dry weight basis), and gluten content (%). All measurements were carried out in triplicate, and the mean values were used for further analysis. The instrument was regularly calibrated in accordance with the manufacturer's guidelines.

2.5. Statistical Analysis

Statistical analyses were performed using JMP Pro 17.0.0 (SAS Institute Inc., Cary, NC, USA). All data are presented as the means. To assess the effect of electron beam irradiation doses (0, 1, 2, 3, 4, and 5 kGy) on cereal grain quality parameters (protein, moisture, and gluten content), a one-way analysis of variance (ANOVA) was conducted. Where significant differences were found ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) post hoc test was applied to identify statistically different group means. Exponential regression modeling was applied to dose–response data for QMAFAnM, mold, and yeast.

The obtained inactivation curves demonstrated an exponential decrease in microbial counts with increasing radiation dose, consistent with the classical model of microorganism inactivation. Accordingly, the relationship between the reduction in the number of mesophilic aerobic and facultative anaerobic microorganisms and the applied radiation dose was described using an exponential mathematical model of the form (1):

$$\text{CFU} = a \cdot e^{-b \cdot D} + c \quad (1)$$

where CFU—the microbial load in colony-forming units (CFU/g);

D —the radiation dose (kGy);

a —initial level of contamination (scale factor);

b —rate of decrease in microbiological contamination;

c —residual CFU value.

To construct an exponential decay model for microbial inactivation, the average CFU values were calculated across all cereal grain samples for each irradiation dose. Additionally, the average percentage reduction in microbial contamination was determined to quantify treatment efficacy.

To identify the mathematical function that best fits the observed microbial reduction data, numerical approximation was performed using the open-source SciPy library in Python (version 3.11.4). The `curve_fit()` function was employed to estimate the parameters a , b , and c of the exponential decay model (Equation (1)), which minimized the residual sum of squares between the empirical data and the theoretical curve.

In addition, Pearson correlation coefficients were calculated to explore relationships among the physicochemical parameters. To visualize clustering and variance across variables and treatments, principal component analysis (PCA) was performed using JMP's built-in multivariate platform. Exploratory data analysis was conducted using a scatterplot matrix to visualize the relationships among the key quality parameters (protein, moisture, and gluten content) of cereal grains in the control (non-irradiated) group. This multivariate visualization allowed for the identification of trends and potential correlations between traits prior to treatment.

3. Results

The effect of electron beam irradiation on the microbiological contamination of cereal grain samples is summarized in Table 3, which presents the changes in the total viable counts of QMAFAnM following treatment at various dose levels using the ILU-10 accelerator.

Table 3. Dynamics of changes in Mesophilic Aerobic and Facultative Anaerobic Microorganisms (QMAFAnM, 10^3 CFU/g) in cereal grains treated with electron beam irradiation on the ILU-10 accelerator.

Item #	Name of Samples	Control (0 kGy)	1 kGy	2 kGy	3 kGy	4 kGy	5 kGy
1	Wheat (Winter, Sapaly)	Solid growth	11	9.2	3	ND	ND
2	Wheat (Farabi 1)	12	ND	ND	ND	ND	ND
3	Wheat (Winter, soft, Mereke 70)	ND	ND	ND	ND	ND	ND
4	Triticale (Elite Kozha, Harvest 2024)	ND	ND	ND	ND	ND	ND
5	Wheat (3rd grade)	4	ND	ND	ND	ND	ND
6	Wheat (Glassy 24)	14	3.8	1	ND	ND	ND
7	Wheat (Egemen 20, 1 reproduction, autumn)	48	17	8	5	4.8	ND
8	Wheat (Kazakhstan 10, 1 reproduction autumn/summer)	37	13	7	5	3.5	ND
9	Wheat (Glassy 24, elite, autumn)	Solid growth	6	4	2	2	ND
10	Wheat (Winter, Kazakhstan)	7	3	3	1	ND	ND
11	Wheat (Forage)	78	6.8	6.1	5.3	1	ND
12	Barley	81	73	8.1	3.1	2.7	ND
13	Oats	49	6.9	8	2.0	1	ND

ND—not detected.

Figure 3 shows the dependence of the number of mesophilic aerobic and facultative anaerobic microorganisms on the radiation dose for the studied cultures.

Grain varieties that exhibited no initial contamination, namely, wheat (Winter, soft, Mereke 70) and triticale (Elite Kozha, Harvest 2024), were excluded from the modeling process, as their baseline QMAFAnM values were 0 CFU/g and thus not suitable for logarithmic transformation.

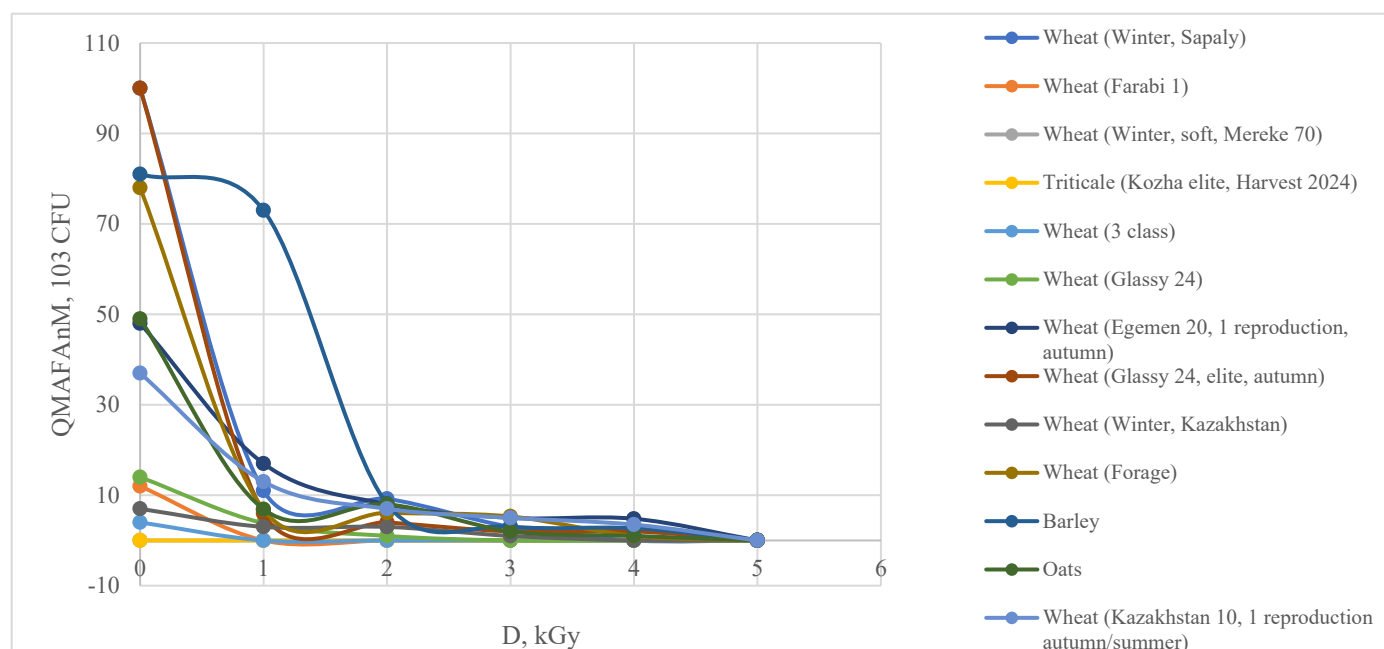


Figure 3. Dependence of QMAFAnM (10^3 CFU/g) levels on irradiation dose (D, kGy) in cereal grain samples treated with electron beam irradiation using the ILU-10 accelerator.

The resulting averaged CFU values and microbial reduction percentages as a function of absorbed dose are summarized in Table 4.

Table 4. Dose-dependent reduction in QMAFAnM (10^3 CFU/g) and average microbial inactivation (%) in irradiated cereal grains.

Name of Samples	Control (0 kGy)	1 kGy	2 kGy	3 kGy	4 kGy	5 kGy
Average QMAFAnM (10^3 CFU/g)	40.77	10.81	4.18	2.03	1.15	ND
Average Microbial Reduction (%)	0	75.41	87.91	94.73	97.44	100

ND—not detected.

Initial parameter estimates were set as follows: $a = 100$ (initial contamination level), $b = 0.5$ (inactivation rate constant), and $c = 0$ (residual contamination level). To avoid bias and singularity issues in the exponential model, the data point corresponding to 0 kGy (i.e., untreated control) was excluded from the model fitting process.

The coefficient of determination (R^2) for the fitted model is 0.995, suggesting that 99.5% of the variation in the observed data is explained by the model. The relationship between microbial load and irradiation dose was best described by an exponential decay model, indicating a significant reduction in QMAFAnM with increasing dose levels (Figure 4).

The parameter $c = 0.073$ represents the residual microbial load, reflecting the asymptotic contamination level at higher doses.

The resulting mathematical model for reducing CFUs is described by Equation (2):

$$\text{CFU} = 26.26 \cdot e^{-0.899 \cdot D} + 0.073 \quad (2)$$

Figure 5 illustrates the average reduction in QMAFAnM contamination (%) in cereal grain samples as a function of the absorbed electron beam dose, highlighting the dose-dependent microbial inactivation trend.

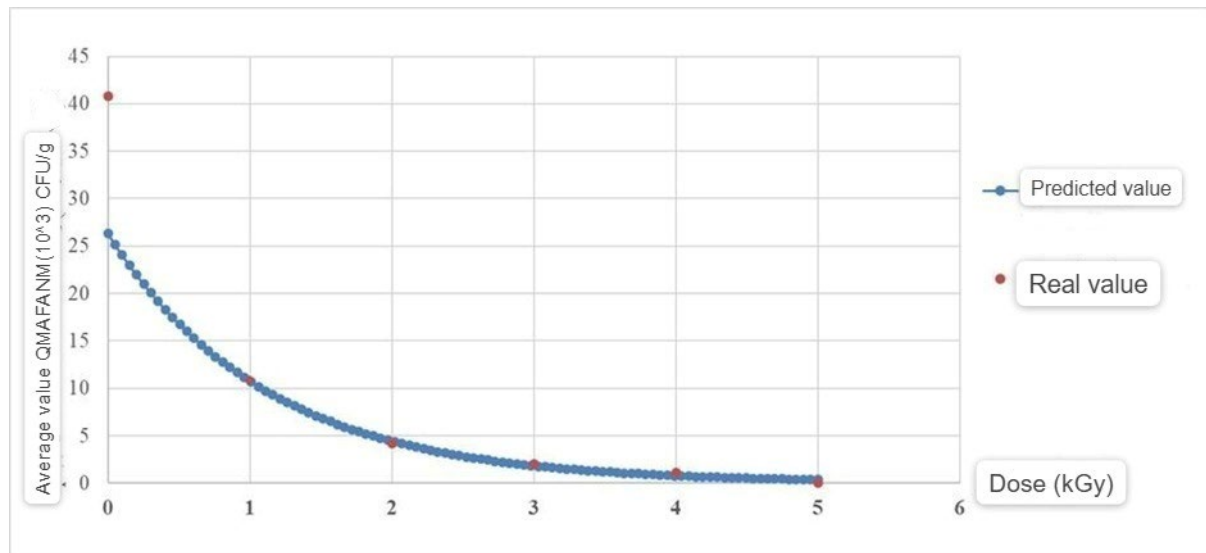


Figure 4. Exponential model of microbiological contamination reduction (QMAFAnM, 10^3 CFU/g) in cereal grains as a function of irradiation dose (kGy).

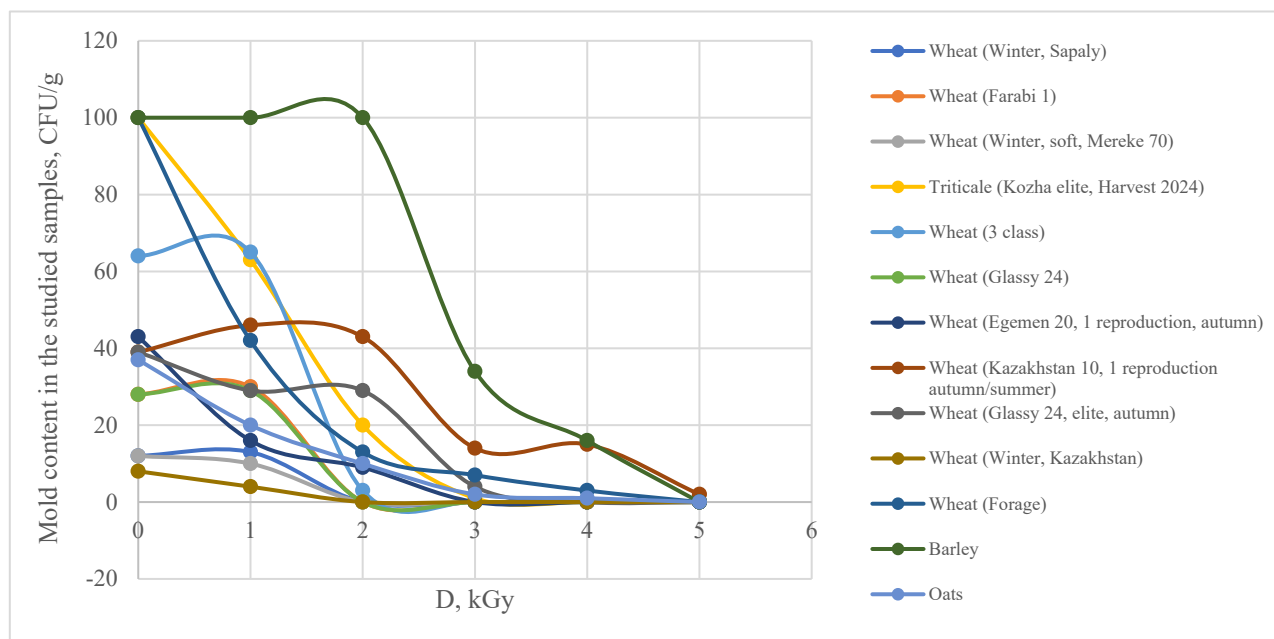


Figure 5. Dependence of mold contamination (CFU/g) on electron beam dose (kGy) in cereal grain samples treated on the ILU-10 accelerator.

Notable differences in radiosensitivity were observed among the cereal crop varieties. For certain samples—such as wheat (Farabi 1), wheat (Mereke 70), and triticale (Elite Kozha)—a significant reduction in QMAFAnM was achieved at relatively low doses of 1–2 kGy. In contrast, more resistant crops—such as barley, oats, and wheat (Egemen 20)—required higher doses to achieve comparable microbial inactivation.

The highest initial levels of microbial contamination were recorded in barley and wheat (Forage), with control group values reaching up to 81×10^3 CFU/g. Nevertheless, electron beam irradiation at a dose of 5 kGy effectively reduced the microbial load in all samples to undetectable levels, confirming the efficacy of high-dose treatment for heavily contaminated grains.

A clear dose-dependent reduction in the QMAFAnM was observed with increasing irradiation intensity. Electron beam treatment at doses of 3 to 5 kGy using the ILU-10

accelerator proved highly effective in significantly decreasing microbial contamination in cereal grain samples.

Table 5 presents the actual average values of mold contamination and the corresponding average percentage reduction across the studied crops as a function of absorbed dose.

Table 5. Dynamics of mold contamination (CFU/g) in cereal grains treated with electron beam irradiation using the ILU-10 accelerator.

Item #	Name of Samples	0 kGy	1 kGy	2 kGy	3 kGy	4 kGy	5 kGy
1	Wheat (Winter, Sapaly)	4	7	ND	ND	ND	ND
2	Wheat (Farabi 1)	16	15	ND	ND	ND	ND
3	Wheat (Winter, soft, Mereke 70)	4	5	ND	ND	ND	ND
4	Triticale (Elite Kozha, Harvest 2024)	100	8	15	1	ND	ND
5	Wheat (3rd grade)	12	15	1	ND	ND	ND
6	Wheat (Glassy 24)	14	14	ND	ND	ND	ND
7	Wheat (Egemen 20, 1 reproduction, autumn)	5	18	18	2	ND	ND
8	Wheat (Kazakhstan 10, 1 reproduction autumn/summer)	18	12	11	5	ND	ND
9	Wheat (Glassy 24, elite, autumn)	5	24	4	ND	ND	ND
10	Wheat (Winter, Kazakhstan)	ND	ND	7	ND	ND	ND
11	Wheat (Forage)	100	6	4	ND	ND	ND
12	Barley	100	100	100	15	8	ND
13	Oats	7	15	ND	ND	ND	ND

ND—not detected.

Table 6 and Figure 6 present the actual average values of mold contamination (CFU/g) and the corresponding average percentage reduction in the mold load for the studied cereal grain samples as a function of absorbed electron beam dose. These results highlight the dose-dependent effectiveness of irradiation in suppressing fungal growth across various crop varieties.

Table 6. Actual average mold contamination values (CFU/g) and average reduction in mold contamination (%) in cereal grains as a function of absorbed electron beam dose.

Name of Samples	Control (0 kGy)	1 kGy	2 kGy	3 kGy	4 kGy	5 kGy
Average Mold Contamination Values (CFU/g)	29.62	18.38	12.31	1.77	0.62	ND
Average Microbial Reduction (%)	0	+54.48	−47.63	−93.02	−99.33	−100.00

ND—not detected.

The graph demonstrates a clear exponential decrease in mold contamination with increasing absorbed radiation dose. A sharp decline is observed between 2 and 3 kGy, beyond which mold levels approach zero. At doses of 4–5 kGy, practical sterility is achieved across all cereal grain samples.

Interestingly, certain samples—such as wheat (Winter, Sapaly), wheat (Farabi 1), and wheat (3rd grade)—exhibited a temporary increase in mold counts following low-dose irradiation (1 kGy).

The most pronounced microbial inactivation occurs in the 3–4 kGy range, where mold reduction exceeds 90%. At 4 kGy, the average reduction reaches 99.3%, and a dose of 5 kGy results in the complete elimination of mold contamination, confirming the effectiveness of electron beam treatment in ensuring microbial safety.

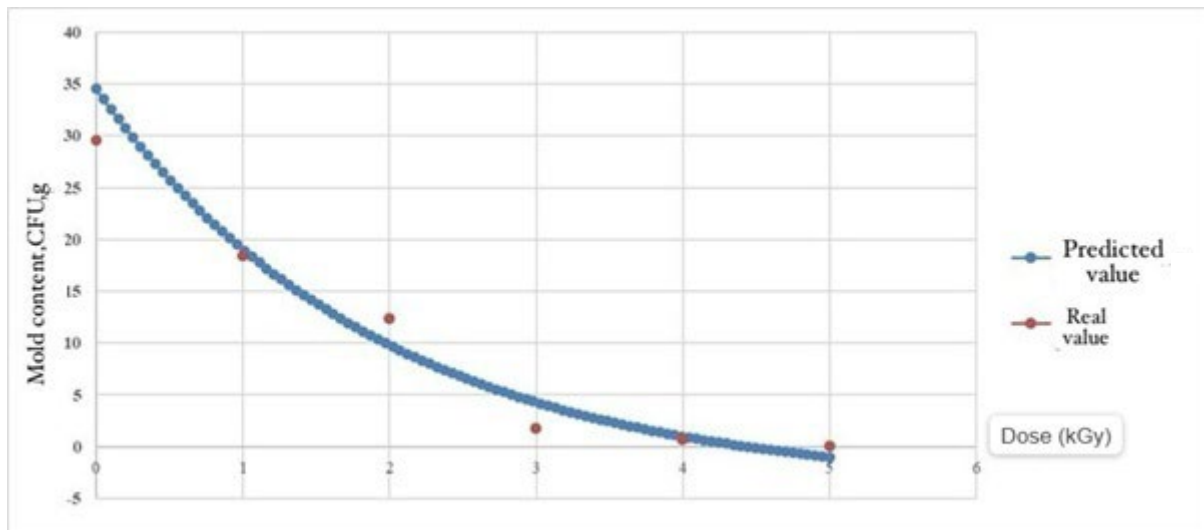


Figure 6. Exponential model of mold reduction (CFU/g) in cereal grain samples treated with electron beam irradiation.

An exponential model of mold reduction depending on the radiation dose was constructed:

$$\text{CFU} = 38.46 \cdot e^{-0.515 \cdot D} - 3.93 \quad (3)$$

Table 7 and Figure 7 present the actual average yeast contamination values (CFU/g) and the corresponding average percentage reduction in yeast load across the studied cereal crops as a function of the absorbed electron beam dose. The data illustrate a clear dose-dependent inactivation trend, confirming the efficacy of irradiation in suppressing yeast contamination.

Table 7. Dynamics of yeast contamination (CFU/g) in cereal grain samples treated with electron beam irradiation on the ILU-10 accelerator.

Item #	Name of Samples	0 kGy	1 kGy	2 kGy	3 kGy	4 kGy	5 kGy
1	Wheat (Winter, Sapaly)	4	7	ND	ND	ND	ND
2	Wheat (Farabi 1)	16	15	ND	ND	ND	ND
3	Wheat (Winter, soft, Mereke 70)	4	5	ND	ND	ND	ND
4	Triticale (Elite Kozha, Harvest 2024)	100	8	15	1	ND	ND
5	Wheat (3rd grade)	12	15	1	ND	ND	ND
6	Wheat (Glassy 24)	14	14	ND	ND	ND	ND
7	Wheat (Egemen 20, 1 reproduction, autumn)	5	18	18	2	ND	ND
8	Wheat (Kazakhstan 10, 1 reproduction autumn/summer)	18	12	11	5	ND	ND
9	Wheat (Glassy 24, elite, autumn)	5	24	4	ND	ND	ND
10	Wheat (Winter, Kazakhstan)	0	0	7	ND	ND	ND
11	Wheat (Forage)	100	6	4	ND	ND	ND
12	Barley	100	100	100	15	8	ND
13	Oats	7	15	ND	ND	ND	ND

ND—not detected.

The dynamics of yeast contamination in response to irradiation demonstrate a dose-dependent reduction trend. At a dose of 1 kGy, changes in yeast levels are minimal; in some cases, a slight increase is observed, which may be attributed to cell reactivation or stress-induced metabolic stimulation. However, at 2–3 kGy, yeast counts exhibit a sharp decline of 90% or more, indicating effective microbial suppression within this dose range, as shown in Table 8.

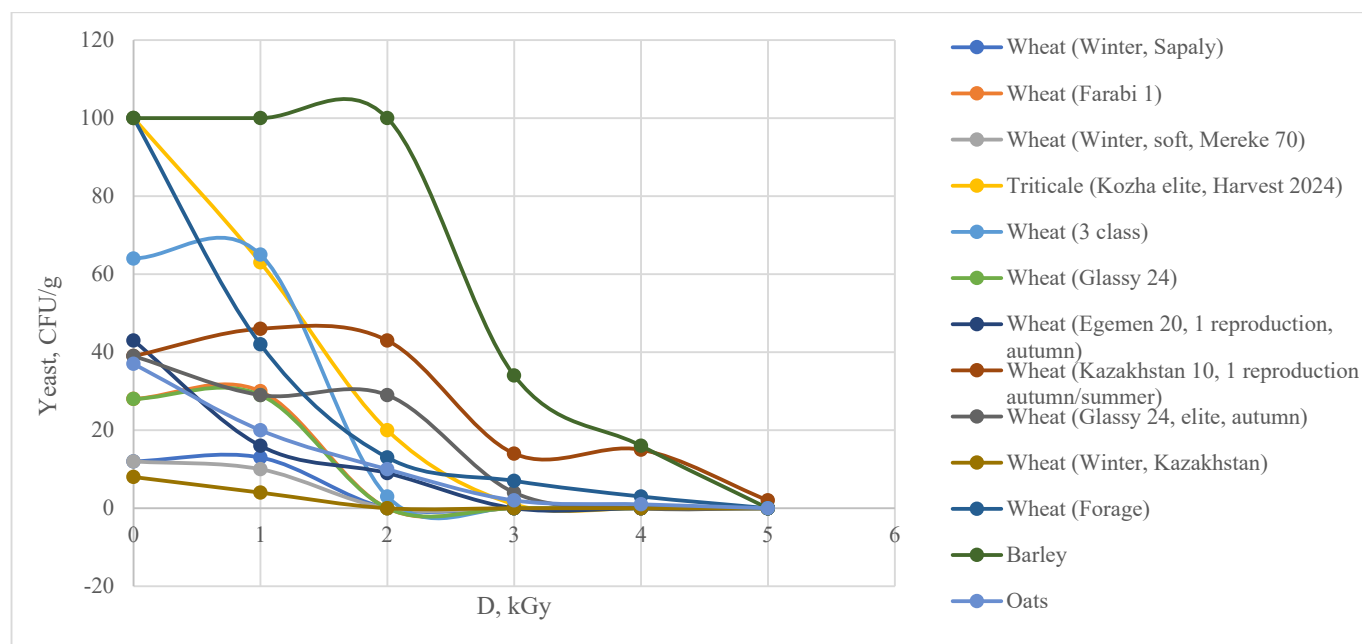


Figure 7. Dependence of yeast contamination (CFU/g) on absorbed electron beam dose in cereal grain samples treated on the ILU-10 accelerator.

Table 8. Actual average yeast contamination values (CFU/g) and average reduction in yeast contamination (%) in cereal grains as a function of absorbed electron beam dose.

Name of Samples	Control (0 kGy)	1 kGy	2 kGy	3 kGy	4 kGy	5 kGy
Average Yeast Contamination (CFU/g)	46.92	35.92	17.46	4.77	2.69	0.15
Average Reduction in Yeast Contamination (%)	0	17.29	69.14	92.20	94.99	99.57

At higher doses of 4–5 kGy, yeast contamination levels approach zero, with most samples achieving practical sterility. The exception was wheat (Kazakhstan 10, 1st reproduction, autumn/summer), where residual contamination was detected.

Figure 8 illustrating the changes in yeast content as a function of the radiation dose were constructed using a logarithmic scale on the Y-axis to enhance visualization of the rapid decline in microbial contamination. The use of the logarithmic scale highlights the sharp drop in yeast counts even at moderate irradiation doses.

On average, a reduction of more than 90% in yeast contamination was observed at 2–3 kGy, indicating a critical threshold for effective microbial inactivation. At 4–5 kGy, the reduction reached 99.57%, approaching the complete elimination of yeast populations in the treated cereal grain samples.

The yeast decay model is approximated by Equation (4):

$$\text{CFU} = 80.07 \cdot e^{-0.738 \cdot D} - 2.10 \quad (4)$$

The application of electron beam irradiation showed a variable but generally stable effect on the protein content of the tested cereal grains (Table 9). Across all dose levels, protein concentrations remained within biologically relevant ranges, with minor fluctuations observed. For example, wheat (Winter, Sapaly) maintained consistent protein values from 16.73% (control) to 16.82% (5 kGy), suggesting that protein stability was not adversely affected by the radiation process. A few samples, such as wheat (3rd grade) and wheat (Egemen 20), exhibited mild dose-related variations; however, no statistically significant

trends of degradation were evident. This confirms that irradiation up to 5 kGy preserves the protein integrity of cereal grains (Figure 9).

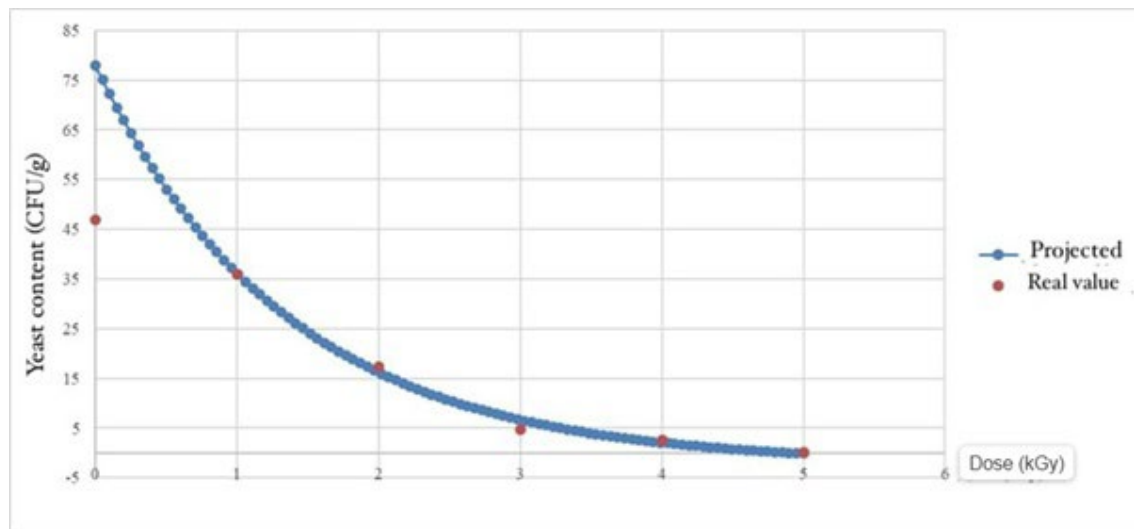


Figure 8. Exponential model of yeast reduction in cereal grain samples treated on the ILU-10 accelerator.

Moisture content showed slight reductions in several samples as irradiation increased, reflecting potential dehydration effects. For instance, in barley, moisture decreased from 10.98% (control) to 10.39% at 5 kGy, while oats showed a similar reduction from 10.60% to 9.37%. In contrast, certain samples like wheat (Farabi 1) and wheat (Winter, Sapaly) displayed relatively stable moisture content across all doses. These results suggest that the electron beam process causes only minor changes in moisture, likely due to controlled irradiation conditions that limit sample desiccation.

Gluten content demonstrated a more pronounced variation among the samples. This pattern was consistent with other wheat varieties such as wheat (Glassy 24) and wheat (Winter, Kazakhstan), where gluten values slightly increased or remained stable with increasing dose. However, in more sensitive varieties like wheat (Kazakhstan 10), a decline was observed from 30.64% to 20.84% across the dose range, suggesting varietal dependence in gluten resilience. These findings imply that moderate doses (2–3 kGy) may enhance gluten extractability or protein network interactions in certain cultivars, without detrimental effects at higher doses.

The relationships between protein, moisture, and gluten content in cereal grain samples were examined using pairwise correlation analysis and were visualized in a matrix plot (Figure 10). The analysis revealed several statistically significant patterns.

A strong positive correlation was observed between protein and gluten content ($r = 0.73$, $p < 0.001$), indicating that samples with higher protein levels tend to exhibit proportionally higher gluten levels.

In contrast, a moderate negative correlation was found between moisture and gluten content ($r = -0.64$, $p < 0.01$), suggesting that samples with higher moisture content generally contained less gluten.

A weak negative correlation between moisture and protein content ($r = -0.33$) was also noted, although this was not statistically significant ($p > 0.05$).

Table 9. Physicochemical properties of cereal grains (protein, moisture, gluten) after electron beam irradiation at various doses on the ILU-10 accelerator.

Item #	Name of Samples	Protein, %						Moisture, %						Gluten, %					
		Control	1 kGy	2 kGy	3 kGy	4 kGy	5 kGy	Control	1 kGy	2 kGy	3 kGy	4 kGy	5 kGy	Control	1 kGy	2 kGy	3 kGy	4 kGy	5 kGy
1	Wheat (Winter, Sapaly)	16.73	16.62	16.48	16.75	16.6	16.82	9.1	9.13	9.28	9.2	9.12	9.12	34.44	33.88	34.21	35.18	33.71 *	34.2 *
2	Wheat (Farabi 1)	16.4	16.36	16.22	16.26	16.21	16.03	8.72	8.87	8.85	8.79	8.85	8.68	32.83	32.09	32.28	32.1	31.64 *	31.31 *
3	Wheat (Winter, soft, Mereke 70)	15.88	15.64	15.57	15.64	15.38	15.64	9.46	9.2	9.16	9.1	9.15	9.07	32.29	30.93	31.02	31.64	30.64 *	30.97 *
4	Triticale (Elite Kozha, Harvest 2024)	11.29	11.41	11.5	11.4	11.55	11.51	9.24	9.23	9.14	9.16	9.15	8.97	21.57	21.56	21.89	22.44	22.17 *	21.81 *
5	Wheat (3rd grade)	14.67	14.55	14.5	14.36	10.85	10.5	9.84	9.74	9.03	8.94	9	8.92	29.49	29.19	28.9	28.29	18.89 *	17.66 *
6	Wheat (Glassy 24)	16.01	16.05	16.5	16.04	16.31	16.25	9.41	9.47	9.16	9.21	9.22	9.17	32.5	32.84	34.83	33	33.24 *	33.64 *
7	Wheat (Egemen 20, 1 reproduction, autumn)	16.61	15.24	15.21	14.89	14.97	14.71	10.24	10.12	9.77	9.31	10.08	9.82	29.75	29.13	31.37	35.62	29.46 *	30.42 *
8	Wheat (Kazakhstan 10, 1 reproduction autumn/summer)	15.15	12.4	12.24	12.2	12.07	11.93	10.56	10.28	10.25	10.14	10.05	9.89	30.64	22.35	21.82	21.68	20.51 *	20.84 *
9	Wheat (Glassy 24, elite, autumn)	14.22	14.1	14.49	14.33	14.2	13.57	9.7	9.51	9.27	9.4	9.37	9.39	27.87	27.81	29.57	28.66	27.45 *	26.03 *
10	Wheat (Winter, Kazakhstan)	17.5	17.41	17.42	17.28	17.49	17.29	9.28	9.19	9.11	9.19	9.14	8.92	36.65	36.96	37.37	36.51	37.1 *	36.75 *
11	Wheat (Forage)	10.5	10.85	10.28	10.64	10.65	10.47	9.84	9.74	9.53	9.66	9.65	9.56	18.89	18.31	18.01	17.66	16.95 *	16.74 *
12	Barley	14.02	13.2	14.18	13.63	14.1	14.15	10.98	10.75	10.66	10.62	10.61	10.39	4.32	4.05	4.31	4.2	3.77 *	4.1 *
13	Oats	11.43	11.19	11.48	11	11.44	10.96	10.6	10.37	9.84	9.82	9.67	9.37	0.37	0.39	0.37	0.37	0.3 *	0.38 *

Values are expressed as the means of triplicates. An asterisk (*) denotes a statistically significant reduction ($p < 0.05$) in quality content compared to the control group.

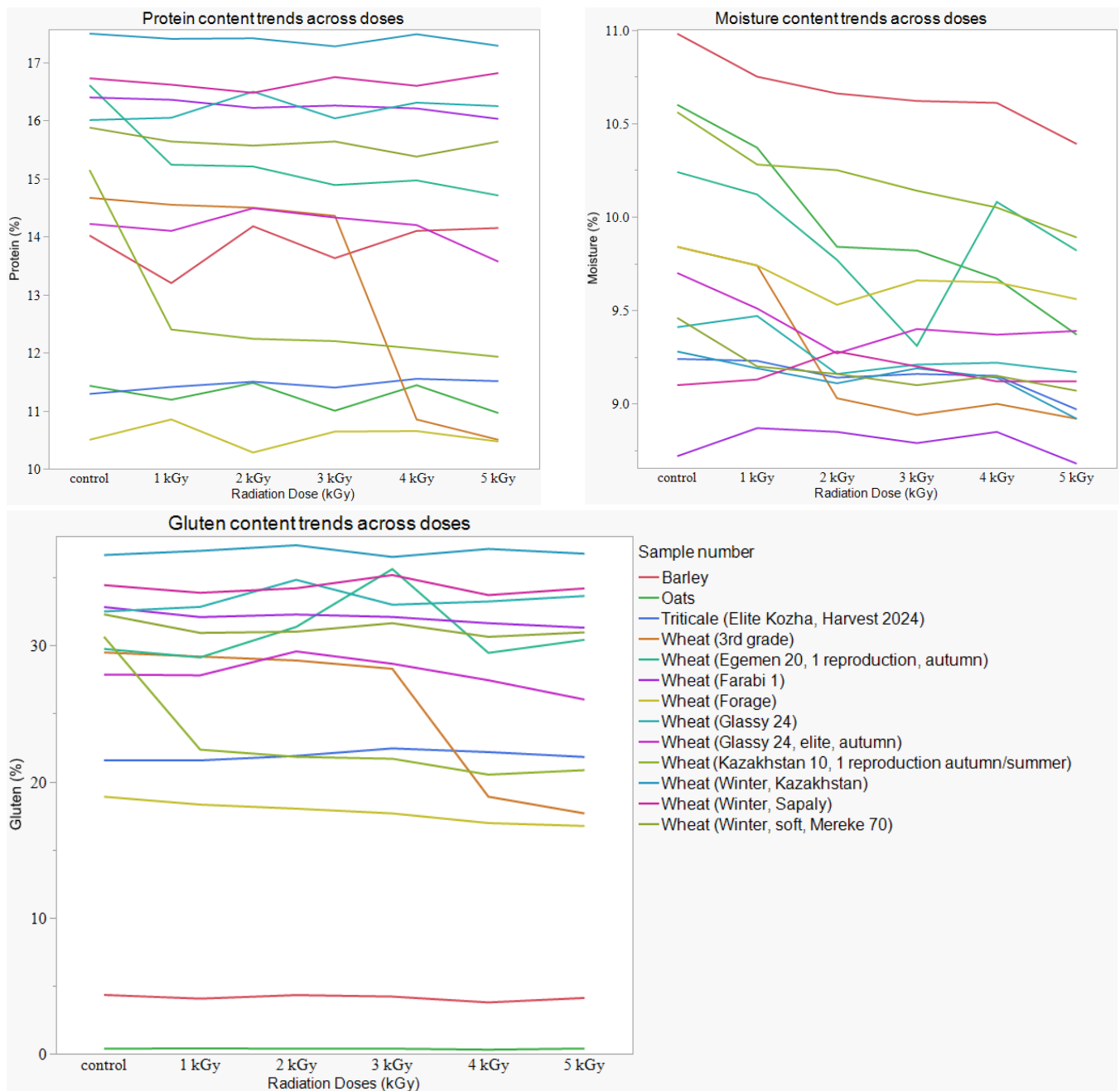


Figure 9. Average protein, moisture, and gluten content in cereal grains by radiation dose and sample-specific trends (0–5 kGy).

The scatterplot ellipses confirm these relationships, illustrating a linear upward trend in the protein–gluten panel and a downward trend in the moisture–gluten panel. Cereal types such as wheat (Winter, Kazakhstan) and wheat (Sapaly) displayed high protein and gluten values, while barley, triticale, and wheat (Egemen 20) were characterized by higher moisture content and lower gluten levels.

To investigate the patterns and associations among protein, moisture, and gluten content in cereal grain samples exposed to varying doses of electron beam irradiation, PCA was performed (Figure 11). The first two principal components (PC1 and PC2) explained 71.7% and 22.4% of the total variance, respectively, accounting for 94.1% of the data variability.

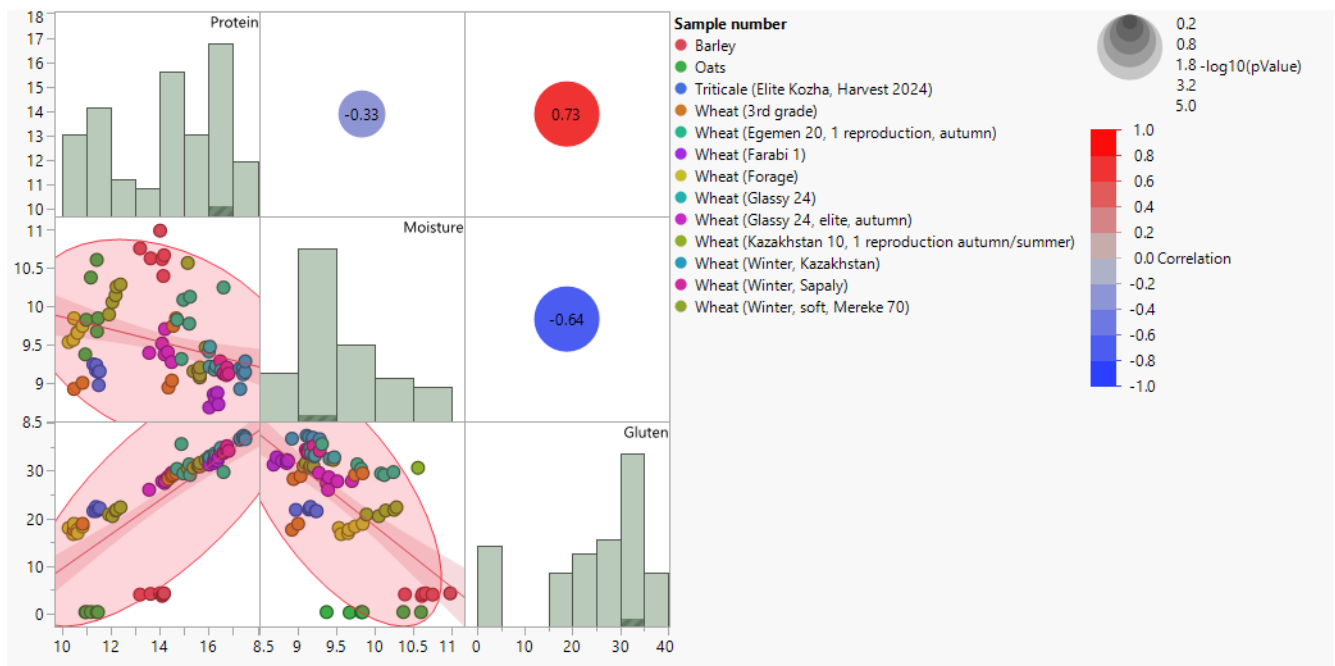


Figure 10. Correlation matrix and distribution plots of protein, moisture, and gluten content in irradiated cereal grain samples. Circle size and color represent the strength and direction of correlation; ellipses illustrate linear regression trends among pairs. Sample numbers correspond to the different crop varieties listed in the legend.

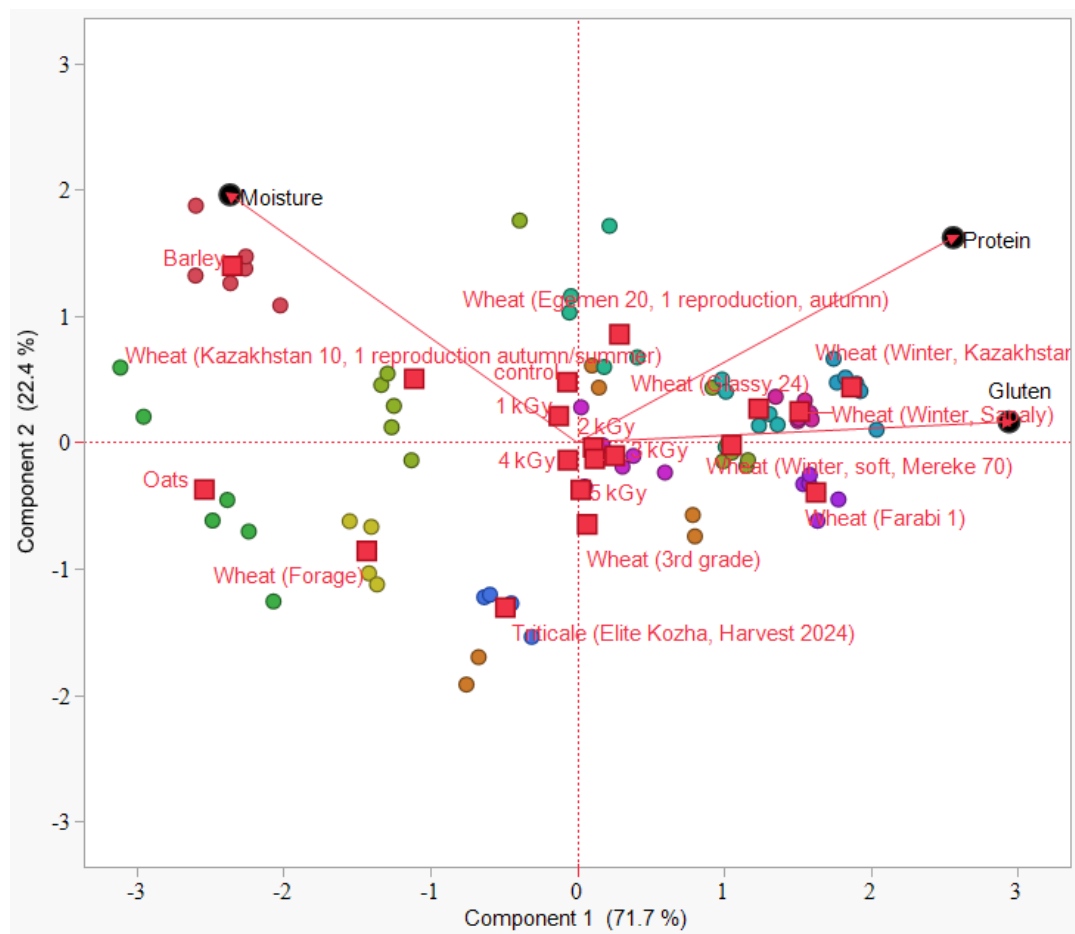


Figure 11. PCA biplot of protein, moisture, and gluten content in cereal grain samples treated with electron beam irradiation.

The PCA biplot reveals clear clustering trends associated with radiation dose and cereal type. The protein and gluten vectors are aligned closely, indicating a positive correlation, which is supported by the Pearson coefficient $r = 0.73$ ($p < 0.001$). Conversely, moisture content demonstrates a negative correlation with gluten ($r = -0.64$, $p < 0.001$) and protein ($r = -0.33$, $p < 0.05$), forming an opposing vector.

The separation of triticale (Elite Kozha) and wheat (3rd grade) along PC2 highlights their distinct physicochemical profile under irradiation.

4. Discussion

The results of this study confirm the high efficacy of electron beam irradiation in reducing microbial contamination—particularly QMAFAnM, molds, and yeasts—in cereal grain samples. Across all studied microorganisms, a clear dose-dependent effect was observed, with significant reductions starting at 2–3 kGy and near-complete inactivation at 4–5 kGy. These findings align with previous studies demonstrating the antimicrobial potential of ionizing radiation in grain decontamination [15,16,26]. The parameters of the exponential model, including a rate constant (b) of 0.899 for QMAFAnM, indicate a rapid decline in microbial load, with contamination levels falling below 5% of the initial count within a radiation dose range of 2 to 3 kGy. At higher doses of 4–5 kGy, microbial presence was nearly eliminated, confirming the effective inactivation of mesophilic aerobic and facultative anaerobic microorganisms. This result is consistent with previous studies demonstrating the dose-dependent exponential inactivation of microorganisms under ionizing radiation [27]. The exponential models fitted to microbial load data (QMAFAnM, mold, and yeast) yielded high coefficients of determination ($R^2 > 0.99$), indicating strong predictive accuracy. For example, the model describing QMAFAnM reduction revealed a rapid decline at doses ≥ 2 kGy, with complete sterility at 5 kGy, consistent with earlier reports that identified electron beam and γ -irradiation as being highly effective for inactivating aerobic and facultative anaerobic bacteria in grains [28,29]. The R^2 value of 0.995 supports its robustness and suitability in describing microbial inactivation kinetics. The current results align with previous findings indicating that electron beam irradiation effectively reduces the microbial burden in cereal grains without compromising essential quality traits. This approach is particularly relevant for grains like triticale, which have been shown to accumulate mycotoxins [30]. The modeled residual contamination parameter ($c = 0.073$) represents the asymptotic microbial load observed at higher radiation doses. This residual level may be attributed to inherent measurement variability or the presence of particularly radiation-resistant microbial subpopulations, which are known to persist even under elevated sterilization conditions [27,31].

Interestingly, a temporary increase in mold and yeast counts was observed in some samples irradiated at low doses (1 kGy), a phenomenon that may be explained by radiation hormesis. This biological effect, whereby low-level stress stimulates cellular repair or metabolic activation, has been reported in microbial systems exposed to sublethal irradiation. Studies have reported that low-dose irradiation (e.g., 1 kGy) can sometimes lead to a temporary increase in mold and yeast counts, likely due to the hormetic stimulation of metabolic activity or repair mechanisms [32]. These findings underline the importance of avoiding subtherapeutic doses in large-scale applications.

Among the grain types studied, wheat (Farabi 1, Mereke 70, triticale) responded to lower irradiation doses, showing the early suppression of microbial contamination. In contrast, barley, oats, and wheat (Forage) exhibited higher baseline microbial loads and required doses ≥ 4 kGy to achieve complete inactivation. These differences could be attributed to grain surface morphology, husk integrity, and natural microbial adhesion, which have been shown to affect irradiation efficacy [33,34]. These findings indicated that

a dose of 2–3 kGy could serve as a crucial threshold for effectively inactivating yeast and mold, with over 90% reduction observed in the majority of instances. This is consistent with previous reports demonstrating the efficacy of moderate-dose gamma irradiation in significantly reducing fungal contamination while maintaining product integrity [35,36].

In practical terms, 2–3 kGy can be considered an optimal range for substantial microbial load reduction (>90%) while maintaining nutritional and physicochemical quality. Higher doses (>5 kGy), although more effective in sterilization, may require further evaluation to assess the impacts on grain texture, germination potential, and nutrient retention, as some studies have noted adverse effects at these levels [37–39].

The dose-dependent variations in protein, moisture, and gluten content across cereal grain samples are illustrated in Figure 9. Protein content trends were generally stable, with a minimal dose-related decline in most samples. However, certain cultivars, such as wheat (Kazakhstan 10) and wheat (Egemen 20), exhibited noticeable protein loss at higher doses, suggesting varietal sensitivity to radiation-induced protein denaturation [40]. A steady decrease in moisture content across almost all samples was observed, likely due to low-level dehydration induced by irradiation. Barley and oats demonstrated significant reductions in moisture, corresponding with their relatively high initial water content and possible structural susceptibility. Conversely, Xue et al. [41] reported that an increase in the moisture of corn flour while applying electron beam irradiation doses ranged between 1.08 and 5.40 kGy. An increase in water solubility of sorghum was reported by Yan et al. [42] when applying electron beam doses between 2 and 10 kGy. Responses to gluten content exhibited notable variation among samples, where some cultivars such as wheat Glassy 24 and wheat Winter Kazakhstan demonstrated either increasing or stable gluten levels, possibly due to enhanced protein extraction following irradiation. Conversely, other cultivars such as wheat Kazakhstan 10 and wheat 3rd Grade had significant declines, suggesting a loss of gluten functionality or protein degradation at elevated doses. These results indicated cultivar-specific responses to electron beam exposure, necessitating precise dose optimization.

In terms of cereal quality parameters, the current findings demonstrate that electron beam irradiation up to 5 kGy has a minimal effect on protein and moisture content, consistent with other studies [43,44]. While gluten content remained relatively stable for most wheat samples, a slight decline was observed at higher doses in sensitive varieties. Previous investigations have also reported slight changes in functional wheat properties at doses above 5–10 kGy due to alterations in protein cross-linking and starch–protein interactions [45,46]. The PCA biplot illustrates the clustering of samples treated at ≥ 4 kGy along PC1, which correlated with elevated protein and gluten levels. Conversely, control and low-dose samples, especially barley and oats, grouped along axes linked to elevated moisture levels. The positive correlation between protein and gluten ($r = 0.73$) and the negative correlation between moisture and gluten ($r = -0.64$) aligned with the principal component loadings. The observed patterns indicated a positive correlation between protein content and gluten levels. This is likely due to the structural role of gluten-forming proteins, specifically gliadin and glutenin, within the overall protein fraction. High-protein varieties, such as Winter wheat from Kazakhstan and Sapaly wheat, contain the highest levels of gluten, thereby supporting this concept. The negative correlation between moisture and gluten/protein indicated that increased water might reduce protein levels or inhibit gluten formation. This trend was particularly pronounced in barley and triticale, which consistently exhibited elevated moisture levels and reduced gluten levels. The proximity of higher-dose samples (≥ 4 kGy) along the protein/gluten axis in the PCA biplot indicated a potential increase in the availability or extractability of the protein network with increasing dose. Irradiation might induce protein solubility [47]. Electron beam treatment could in-

duce protein unfolding or partial denaturation, potentially facilitating the growth of certain types of gluten. Refs [48,49] showed that electron beam treatment up to 30 kGy resulted in the unfolding of rice proteins. Gluten remained stable or increased slightly in samples such as wheat (Glassy 24) and wheat (Winter, Kazakhstan). The PCA plot exhibited unusual behavior, particularly in the separation of wheat (3rd grade) and triticale (Elite Kozha), indicating that various genotypes responded to radiation differently. Wheat exhibited a significant reduction in gluten content at elevated doses, while the protein levels in triticale remained unchanged. However, it exhibited low gluten levels, likely due to its classification as a wheat–rye hybrid, which inherently possesses a reduced gluten potential.

These results support the broader implementation of accelerated electron beam treatment as a sustainable, non-chemical method for grain sanitation, in line with FAO (2019) recommendations on reducing post-harvest losses and food waste. Nevertheless, further studies should explore strain-specific resistance, especially for molds and yeasts, and characterize residual viability following exposure to high irradiation levels.

5. Conclusions

The present study demonstrates that electron beam irradiation is an effective non-thermal method for reducing microbiological contamination in cereal grains. The degree of inactivation of microorganisms was dose-dependent, with QMAFAnM showing the highest sensitivity, followed by mold and yeast.

At 1–2 kGy, significant microbial reductions were observed; however, in some samples of mold and yeast, a temporary increase in counts occurred, likely due to radiation hormesis. At 3–4 kGy, microbial populations declined exponentially, and at 5 kGy, nearly complete sterilization was achieved, with 100% reduction in QMAFAnM and mold, and 99.68% reduction in yeast, leaving only trace amounts (0.15 CFU/g).

Visual and quantitative data suggest that yeast populations exhibit greater resistance to irradiation than other microbial groups, while the QMAFAnM is most susceptible. The optimal dose for practical application, ensuring >90% microbial reduction while preserving grain quality, lies in the range of 2–3 kGy. For complete sterilization, 4–5 kGy is required.

In addition to microbial decontamination, the evaluation of quality parameters—such as protein content, moisture, and gluten—demonstrated that irradiation at doses up to 5 kGy did not cause the significant degradation of these critical nutritional and technological traits. Protein content remained stable, while changes in moisture and gluten were minimal and statistically insignificant.

These findings support the implementation of electron beam irradiation as a sustainable and efficient technology for ensuring the microbiological safety of grain crops, reducing post-harvest losses, and extending storage life without the use of chemical preservatives.

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Abbreviations

The following abbreviations are used in this manuscript:

QMAFAnM	Quantity of Mesophilic Aerobic and Facultative Anaerobic Microorganisms
FAO	Food and Agriculture Organization
IAEA	International Atomic Energy Agency
WHO	World Health Organization
PSS	Peptone salt solution
CFUs	Colony-forming units
ANOVA	Analysis of variance
PCA	Principal component analysis

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