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ORIGINAL ARTICLE

Impact of UV-C irradiation on storage pests with different ecological functions and the viability of the treated grains

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Abstract

This study was carried out to investigate the effect of different exposures of UV-C radiation (253.2 nm) (5, 10, 15, 20 and 25 mins) on the mortality of adult stages of four stored product pests: *Sitophilus granarius* L. (Coleoptera: Curculionidae) as a primary pest, *Tribolium castaneum* (Herbst) (Col.: Tenebrionidae), *Cryptolestes ferrugineus* (Stephens) (Col.: Laemophloeidae) and *Oryzaephilus surinamensis* (Ganglbauer) (Col.: Silvanidae) as secondary pests. Additionally, the viability of treated maize and wheat grains influenced by UV-C radiation (10 mins of UV-C at a distance of 22 cm) was analyzed by using a tetrazolium test. Insect rearing was carried out at 26 ± 2°C, 60 ± 7% RH, 16/8 photoperiod. Our results confirmed that a longer exposure (25 min.) to UV-C corresponded with higher mortality over time. In the elapsed time after radiation treatment as a function of exposure, the mortality was characterized by a power trend line for each examined insect species. *S. granarius*, as the primary stored product pest, in the crop treated by shorter exposure may prevent subsequent infestation of secondary stored product pests (*T. castaneum, C. ferrugineus, O. surinamensis*). The tetrazolium test showed that wheat seeds were more sensitive to UV-C radiation than maize seeds. This pest elimination technique is primarily recommended in environments exempted from viable stored seeds. UV-C irradiation of stored products could be an effective non-chemical practice against arthropod pests that move on the surface.

Keywords: primary pest, secondary pest, stored grain, treated seed viability, ultraviolet radiation

Introduction

Stored product arthropod pests can cause significant damage in many parts of the world in cereals and other crop items stored in warehouses. These quantity damage proportions triggered by pests are estimated to be around 9% in developed and as high as 20% in developing countries (Phillips and Throne 2010). In the Carpathian Basin, more than 100 insect species damaging stored products can occur in grain warehouses. The most common are: *Sitophilus granarius* L., *S. oryzae* L. (Coleoptera: Curculionidae), *Tribolium castaneum* Herbst, *T. confusum* Jacquelin du Val (Col.: Tenebrionidae) *Oryzaephilus surinamensis* L., *Cryptolestes ferrugineus* Stephens) (Col.: Silvanidae) (Novák 2014), *Sitotroga cerealella* (Olivier) (Lep.: Gelechiidae) and *Ephestia kuhniella* (Zeller), *E. elutella* (Hübner) (Lep.: Pyralidae) (Schöller and Prozell 2014).

The damage caused by stored insect pests occurs continuously under storage conditions, sometimes causing severe post-harvest loss. Chemical action against them is a practical, regularly accepted element in Central Europe (Stejskal *et al*. 2015).

Several insect species are responsible for the damage caused, and their species composition in stored items are crucial determinants of the extent of the damage. These pests can be grouped in several ways based on their functional classification and their presence in these items (Nayak and Daglish 2018). Thus, primary pests such as *Sitophilus* spp. or *Rhyzopertha dominica* (Fabricius), open a pathway through the seed coat. Their larvae, which are hidden, develop in the seed and continue the damage initiated by the imago. They are followed by secondary pests, *e.g., Cryptolestes ferrugineus* or *Tribolium* spp. which can colonize and develop visibly on the damaged grain. Eventually, the facultative storage pests, mold-eaters, degradative facultative necrophagous and predators will emerge (Schöller and Prozel 2014). The successive emergence of organisms with different ecological roles in stored batches will clearly cause increasingly severe and widespread damage.

A difficulty in chemical stored product pest control is the small number of effective agents available (Hagstrum and Phillips 2017). Additional problems are that these agents may also be highly toxic to vertebrates, their degradation products can appear in treated foods, and there is a risk of insecticide resistance due to their regular use (Hagstrum 2016). To address these facts and to meet the criteria of sustainable agricultural production, alternative, chemical-free control methods and their experimental laboratory analysis are becoming increasingly important in managing agricultural pests (Arthur 1996; Boyer *et al.* 2012). Several approaches to these control methods are known, such as the use of inert dust, diatomaceous earth, *etc*. (Shah and Khan 2014; Ziaee *et al*. 2021), the addition of essential oils and other natural compounds (Golob *et al*. 1999; Campolo *et al*. 2018), and stored product treatments with electromagnetic radiation of different wavelengths (Hallman 2013).

There have been many radiation experiments, and results have been published on stored product pests using different wavelengths of radiation (Abdelaal and El-Dafrawy 2014; Mazima *et al*. 2018). Ionizing radiation is composed of subatomic particles or electromagnetic waves with sufficient energy to ionize atoms or molecules by removing electrons. Some particles can reach 99% of the speed of light. They have a wavelength of 100 nm or less or a frequency of 1.1015 Hz. The higher energy ultraviolet part of the gamma, X-ray and electromagnetic spectrum is ionizing radiation (Ryan 2012). Successful control has been carried out with, e.g., ultraviolet (Hasan and Khan 1998; Azizoglu *et al*. 2011), X-ray (Tsan *et al*. 2003; Indiarto and Qonit 2020) and gamma radiation. A critical consequence of these studies, which can limit their practical application, may be a reduction of the nutrient content of the grain to be protected, in addition to the target pest species, and the reduction of seed germination capacity through the influence on embryo viability (Lacroix and Follett 2015; Han *et al*. 2018). Regardless of these advantages and disadvantages, alternatives to chemical-free control are becoming more and more important today. Research into these methods and analysis of their consequences is at the heart of modern crop protection research.

We have reported on the results of our studies on the effects of different wavelengths of electromagnetic irradiation on storage pests in several publications (Keszthelyi *et al*. 2015, 2021; Keszthelyi and Pal-Fam 2019). These testing approaches have mainly been directed against adult stages, as it is difficult to assess the involvement of latent developmental stages of some species (Bakri *et al*. 2021). UV-C treatments, which include ionizing radiation, may be most suitable for surface treatment due to their low penetration (Andersen *et al*. 2006). There is little information available on practical applications of the technique, either directly or in combination with other methods.

Based on this background, our laboratory studies aimed to assess stored product pests' exposure with different ecological functions – as primary (*S. granarius*), secondary (*T. castaneum*, *C. ferrugineus*) and predator (*O. surinamensis*) species – to UV-C ionizing radiation. A further objective was to determine the mortality responses of each species and the differences between them. We also wanted to investigate the extent to which UV-C irradiated seed items change in germination. The results of these studies were expected to confirm our preliminary hypothesis, *i.e.,* the potential effectiveness of this physical method against target pests and preservation of the germination capacity of the crop to be protected.

Materials and Methods

Insect culture and maintenance

Four stored product pest species with different ecological functions were used for our radiation test. *Sitophilus granarius* was the primary pest, and *Tribolium castaneum*, *Cryptolestes ferrugineus* and *Oryzaephilus surinamensis* were secondary pests. The experimental species' laboratory cultures originated from our Institute of Agronomy in Kaposvár Campus of the Hungarian University of Agronomy and Life Sciences of the MATE.

Sitophilus granarius was reared on wheat grains (moisture content: 13.5%). *T. castaneum*, *C. ferrugineus* and *O. surinamensis* were reared on wheat flour mixed with yeast (10:1, w/w). The culture was maintained under optimal conditions for the insect in a climate chamber. Insect rearing was carried out at 26 ± 2°C, 60 ± 7% RH, 16/8 photoperiod. The age and the sex of adult insects used in radiation experiments were mixed in order to reflect real conditions in the field. Untreated, healthy wheat grains (moisture content: 13.5%) were used for the experiment. Each treatment during this laboratory examination was carried out under the same experimental settings.

Apparatus and methodology of UV-C radiation

Brenner UVC-30 (E27) type ultraviolet UV-C germicidal lamps (Brenner GmbH & Co. KG. Mühlweg 5 89407 Dillingen-Fristingen Germany) were used for the radiation experiment with physical parameters: nominal wavelength 253.7 nm, 30W, 220-240 V, 50 Hz. Four UV-C germicidal lamps were placed 22 cm apart on a stand directly next to each other, as shown in Figure 1.

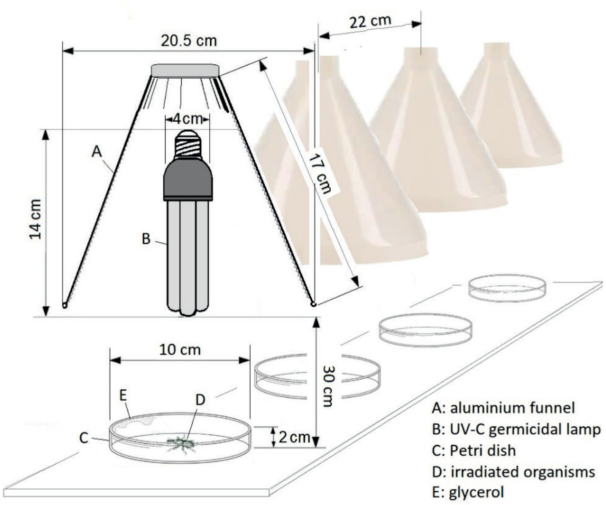

Fig. 1. Parameters of the ultraviolet-C radiation setting

In each case, treatments with ultraviolet-C ionizing radiation were carried out at the same distance and under the same physical parameters as the lamp. Five adults of each insect species were placed in Petri dishes, with four replicates per treatment. Before radiation, the rims of the Petri dishes were coated with glycerol to prevent insect escape. In order to avoid other insecticidal effects, the thin layer of glycerol was immediately wiped off after treatment (no dead insects were found stuck in it). Both insect species and seeds were irradiated directly and separately from other organisms. The mortalities of the four insect species were evaluated individually after each treatment. The treatments differed according to the exposure to radiation. Thus, the effects of the radiation exposures of 5, 10, 15, 20 and 25 mins were examined on the mortality of different insect species at 0, 24, 48 and 72 h after radiation (hereafter referred to as "elapsed time after treatment"). They were then put back into the climate chamber after we had measured the "0 h" mortality. In each case, the treated groups were accompanied by an untreated group with similar parameters.

To evaluate the viability of wheat and maize embryos, a tetrazolium test (TZ) was applied, with a developed version of the methodology suggested by Carvalho *et al.* (2013). First-year wheat (variety: Antonius®, Saatbau Linz Hungary Ltd.) and maize (hybrid: DKC4611®, Bayer Crop Sciences) grains were used in the test, with 10-10 seeds per treatment (uniformly: 24 h after treatment). As a first step, seeds were immersed in water (10 ml water/grain, for 6 hours at 20°C) to release the embryo from its ametabolism. The seeds were cut in half lengthwise along the embryo and placed in a plastic container between filter paper discs. Staining was done with a 1.0% tetrazolium solution and placed in an incubator at 30°C for 2 hours.

A slightly modified version of the method recommended by the Association of Official Seed Analysts (AOSA) (2000) was used to test the viability of maize embryos. Maize kernels were soaked in water for 16 hours as a pre-treatment. The seeds were cut lengthwise with a scalpel (Dynarex Medi-Cut) and placed in 0.5% tetrazolium solution in plastic containers. The prepared samples were placed in an incubator at 25°C for 4 hours.

Viable seeds were considered to be those in which the embryo stained bright red uniformly (Fig. 2). Viability ratio (V) of seeds was determined as follows:

$$V = (nv \cdot tn^{-1}) \times 100,$$

Fig. 2. Tetrazolium test results on maize grain. A) corn grain cut in half, B) discolored embryo showing viability

where: nv – the number of viable embryos, and tn – the total number of embryos.

Statistical analysis

The mortality values of each examined species were calculated by Abbott's (1925) formula (M), where: M = [(C-T) · C^{-1}] × 100; where: C – number of survived individuals in the control; T – number of survived treated individuals. The slope descriptors (a) of the linear trend descriptor equation (y = ax + b) fitting the mortality values were determined and compared by species. The recorded mortality values were averaged at defined time points (0, 24, 48 and 72 h) after the treatments to obtain information on the UV-C exposure of the species studied. Equations describing trend lines fitted to the mortality values after each exposure were used to calculate curves representing total mortality, which can be determined by species.

The Shapiro-Wilk test was employed to test the mortality data of stored product pests ($n > 50$). The evaluation of the normal distribution of data was effectuated by Ghasemi and Zahediasl-type methods ($p < 0.05$). A total sample size of 20 for each species was tested. The mortality data were assayed using a two-way ANOVA in SPSS 11.5 software (response variable: adult mortality and grain viability; main effects: exposure and elapsed time after UV-C radiation). The means were analyzed by the Tukey-test ($p < 0.05$). We established the slopes of the linear regression curves for the mortality value series along the radiation exposure time (0, 5, 10, 15, 20, 25 mins) and the elapsed time after treatment (0, 24, 48, 72 hours) and the directions of the changes that belonged to the most relevant effects.

Moreover, each species' theoretical total mortality curves were extrapolated from the equations of calculated mortality trendlines ($p < 0.05$). The extrapolation was based on power-type equations describing the recorded mortality trends for each species, using the exposures used in the experiment. The points in the diagram represent coordinates describing the total extinction of the experimental insect population

The Abbott-corrected mortality (Abbott 2025) data were subjected to a correlation analysis by species as a function of exposure to UV-C radiation and the elapsed time after treatment in order to understand the similarity of the mortality responses to irradiation between species.

Results

Effect of UV-C radiation on insect mortality

The results of the two-way ANOVA for each species included in the experiments confirmed that both exposure times (*S. granarius*: df = 4, F = 16.759, $p < 0.001$; *T. castaneum*: df = 4, F = 34.444, $p < 0.001$; *C. ferrugineus*: df = 4, F = 45.415, $p < 0.001$; *O. surinamensis*: df = 4, F = 18.785, $p < 0.001$) used and the elapsed time after treatment (*S. granarius*: df = 5, F = 82.230, $p < 0.001$; *T. castaneum*: df = 5, F = 35.444, $p < 0.001$; *C. ferrugineus*: df = 5, F = 64.661, $p < 0.001$; *O. surinamensis*: df = 5, F = 117.80, $p < 0.001$) had a statistically verifiable effect on the mortality values recorded.

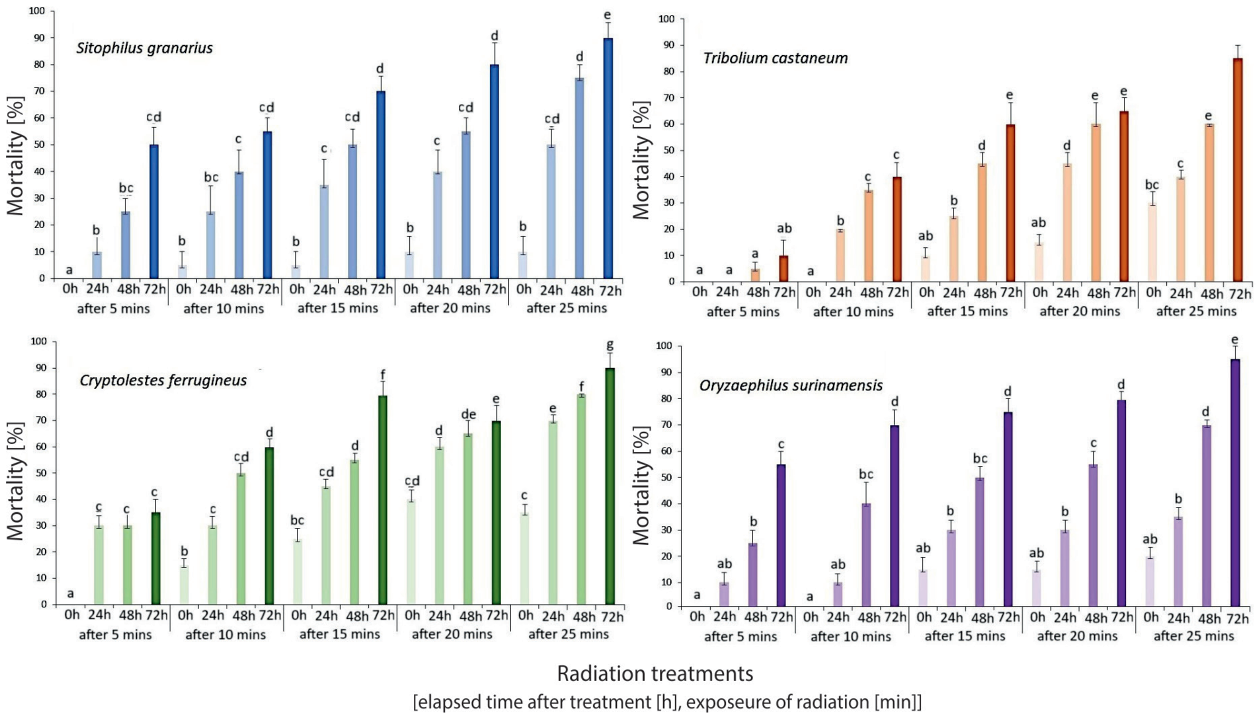

Fig. 3. Abbott corrected mortalities (mean ±SE) of different stored product pests as a function of exposure of radiation and elapsed time after treatment

The Abbott-corrected mortality values of UV-C irradiation on storage pests are shown in Figure 3. It can be observed that exposure to radiation increased the mortality values in a species-dependent manner. Irrespective of the radiation exposure, it can be concluded that the time elapsed after treatment is crucial for the development of the mortality values of the targeted pest population. The mortality-inducing consequences of lethal doses and exposures can be objectively assessed at the earliest at 48 to 72 hours after treatment. The highest mortality values for all treatments for all species was recorded 72 hours after radiation. In some cases, even shorter exposure to radiation induced high mortality (such as *C. ferrugineus* in the 72 h observations of 15 min radiation). Without exception, the most prolonged exposure to radiation caused the highest mortality (72 hours after 25 minutes of radiation exposure) in all of the examined species. These values increased over time after treatment.

When the individual exposures were examined as a function of time elapsed after treatment, it was found that the mortality values over time increased linearly. The mortality trends recorded for the different insect species differed slightly. The most significant increase observed with time after each treatment was recorded for *O. surinamensis*. The value (a) of the linear trend line fitted to the mortality values describing the slope of the increase was found to be highest for this species (a: 3.466) In contrast, the lowest increase in mortality during the observation period following radiation was observed in *C. ferrugineus* (a: 2.751), while for the other species they developed as follows: *S. granarius*: 2.819, *T. castaneum*: 3.176.

Average Abbott-corrected mortality values showed that UV-C radiation caused the most significant mortality in *C. ferrugineus* (mean mortality per control session: 38.6%). In comparison, the mortality of *T. castaneum* had the least effect (26%). Interestingly, *S. granarius* and *O. surinamensis,* although with different process characteristics, responded with similar average mortality (31.2%) to radiation.

The time points following exposure to UV-C irradiation of the experimental insect species for different durations and the trend lines connecting them are shown in Fig. 4, along which the total mortality of the species can be expected. In all cases, the calculated mortality rates are best described by a power trend line, which is well illustrated by the R^2 values indicating the strength of the correlation. It can be seen that the time period following the treatment which led to total mortality was inversely proportional to UV-C radiation. The longer the exposure of an arthropod to ionizing radiation, the shorter the period before the experimental population perished. The time of complete death in the post-treatment period, depending on the radiation exposure, can be described with an exponential trend line for all investigated insect species.

The sensitivity of the different species to UV-C radiation is also clearly shown in the analysis of the graph. A statistically verifiable difference was confirmed by the results of the two-way ANOVA (df = 3; F = 34.162; $p < 0.001$). According to our experimental results, based on the mortality during the period following UV-C radiation, the following order of susceptibility can be established from the most

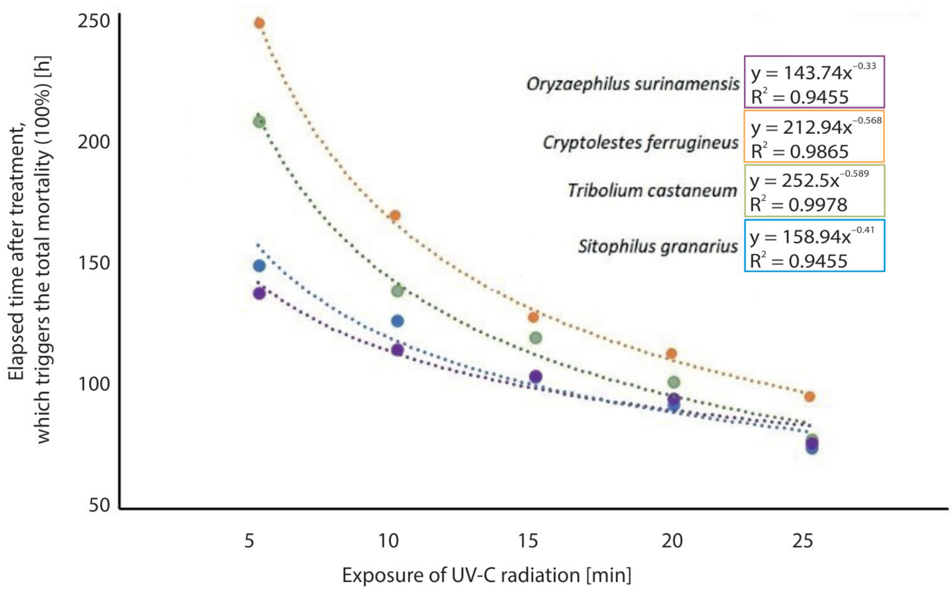

Fig. 4. Elapsed time after different UV-C irradiation exposures, which triggered the total mortality (LD_{100}) of experimental stored product pests

susceptible to the most resistant species: *O. surinamensis, S. granarius, S. ferrugineus* and finally, *T. castaneum*.

The mortality value varied almost in direct proportion to exposure and time elapsed after treatment (Fig. 3). The changing trend can be well approximated by the slope of the fitted linear curves, whose values are shown in Fig. 5. The curves are flatter along the exposure time, *i.e.*, the slope of the mortality curves is smaller, and the interspecific variance is more diminutive. The elapsed time after treatment significantly influenced the mortality value, and the variation between species was more significant.

The strength of the relationship between species' mortality values is shown in Table 1. There was a strong relationship in mortality values with exposure time between *S. granarius* and *C. ferrugineus* (correlation coefficient was 0.945) and between *T. casteneum* and *C. ferrugineus* (correlation coefficient was 0.939). The close correlation between *S. granarius* and *C. ferrugineus* suggests that these species had similar sensitivities to UV-C irradiation. Intervention with UV radiation against the primary pest species may result in the co-eradication of any secondary pest species that may accompany it. There was a medium relationship between *S. granarius* and *O. surinamensis* (correlation coefficient was 0.873) and *C. ferrugineus* and *O. surinamensis* (correlation coefficient was 0.842). In contrast, the most substantial relationship in mortality by elapsed time after treatment was between *S. granarius* and *C. ferrugineus* (correlation coefficient was 0.756).

Effect of UV-C irradiation on seed viability

The changes in embryo viability of maize and wheat

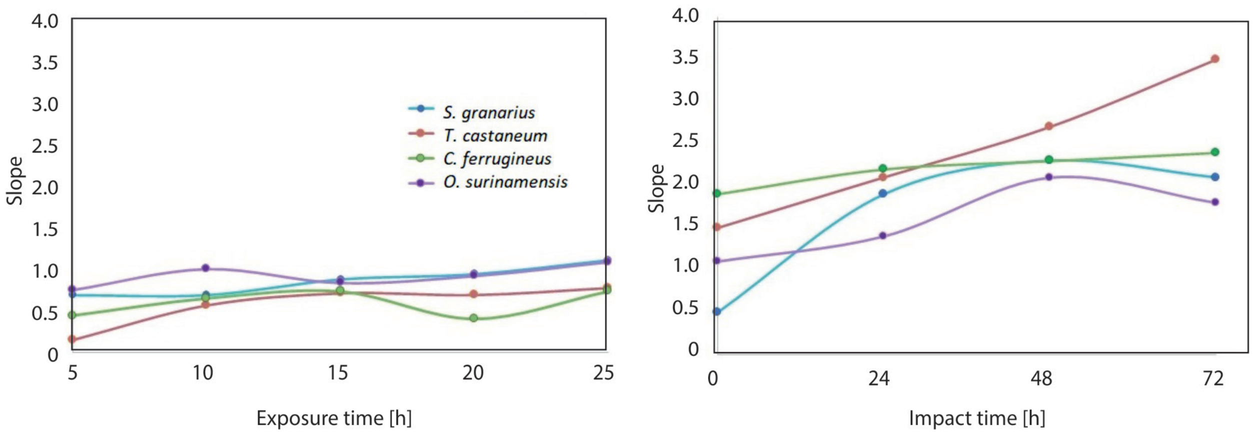

Fig. 5. Slopes of the fitted linear functions based on a) the exposure time (the linear regression functions and so the values of the slopes varied along the time elapsed after treatment) and based on b) the elapsed time after treatment (the linear regression functions and so the values of the slopes varied along the exposure time). Explanation: the plotted points are the slope term (a) of the growth trend formula (y = ax + b)

Table 1. Correlation matrices detected the intensity of the mortality value. The correlations are higher in the case of the a) exposure time than in the case of b) elapsed time after treatment

	Exposure time [min] (a)			
	Sitophilus granarius	*Tribolium castaneum*	*Cryptolestes ferrugineus*	*Oryzaephilus surinamensis*
Sitophilus granarius	1	–	–	–
Tribolium castaneum	0.784	1	–	–
Cryptolestes ferrugineus	0.945	0.939	1	–
Oryzaephilus surinamensis	0.873	0.781	0.842	1
	elapsed time after treatment [h] (b)			
Sitophilus granarius	1	–	–	–
Tribolium castaneum	0.756	1	–	–
Cryptolestes ferrugineus	0.332	0.550	1	–
Oryzaephilus surinamensis	0.577	0.694	0.493	1

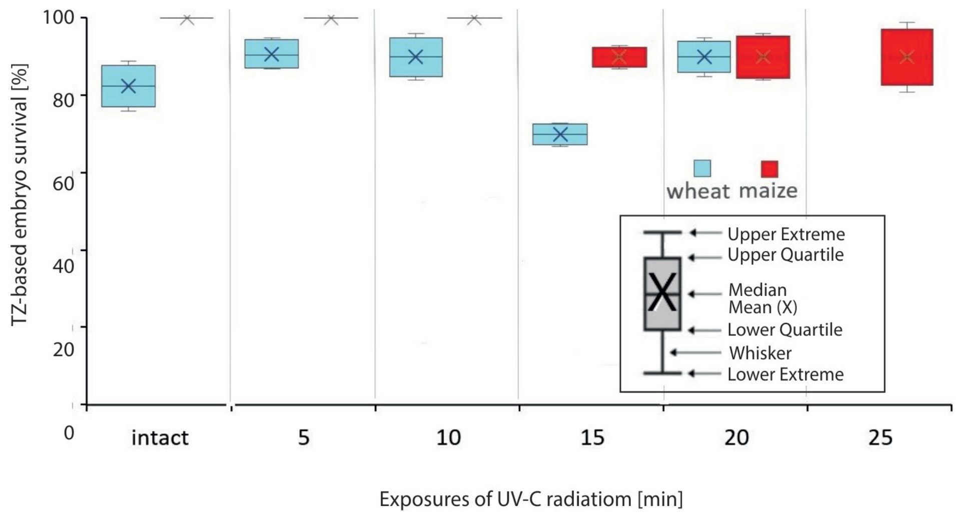

Fig. 6. Tetrazolium test based embryo survival of wheat and maize grains at 24h elapsed time after different exposures to UV-C radiation

seeds in response to UV-C radiation are shown in Figure 6. Different exposure radiations can cause variations in the viability of different plant seeds. In addition, there were differences in the viability of seeds of different species. The TZ test showed that the wheat seeds were more sensitive to this physical stress than maize seeds under similar conditions. In the most extreme case, 15 minutes of UV-C exposure resulted in a 30% reduction in the viability of the wheat kernels. Values of the recorded viabilities fluctuated highly, and the trend of the changes could not be defined. Nevertheless, the significant effect of exposure to ionizing irradiation on grain viability was confirmed (df = 5; F = 16.177; $p < 0.001$). The difference in the considerable effect of UV-C irradiation on the viability of different seeds was confirmed by the results of the two-way ANOVA (df = 1; F = 84.100; $p < 0.001$), while the combined effect of the two factors on viability was also confirmed (df = 5; F = 5.644 $p < 0.001$).

Discussion

Our results demonstrated the insecticidal effect of UV-C ionizing irradiation on stored product pests, which can be an effective solution to the problem of stored product pests. Our experiment confirmed several results of previous research (Meng *et al.* 2009; Sedehi and Karbalaizadeh 2014; Akhila *et al.* 2021). UV-radiation is an effective protection method against various storage insects such as *T. castaneum*, *T. confusum* and *S. cerealella* (Akhila *et al.* 2021; Ameri *et al.* 2021).

Several varieties of practical insect management options, such as physical, mechanical, biological, and chemical methods, are available. For example, fumigation has been applied in storage as a dominant method for decades (Guru *et al.* 2022). However, opportunities for fumigation and classical chemical methods are narrowing after the phase-out of methyl bromide and chlorpyriphos (Daglish *et al.* 2018). At the same time, sustainable and environmentally friendly approaches have been developed which make non-chemical management practices possible. Different wavelength electromagnetic radiations are a part of these opportunities. Among these, several studies report on the effectiveness of ionizing radiation (wavelengths below 280 nm) against storage pests under laboratory conditions (Musil *et al.* 1998; Hallman 2013; Bakri *et al.* 2021).

Different radiation techniques have many non-chemical benefits such as atmospheric freezing or heating, easy operation of irradiators, and quick triggered mortality. However, these require higher initial costs as well as higher dosages that pose a risk to human health (Hasan and Khan 1998).

In our experiment, we have pointed out that different pest species showed variations in their sensitivity to this physical effect. Regardless of the radiation exposure, mortality rates following immediate treatment were low or non-existent for all insect species. Due to the physiological effects of radiation, faster, higher mortality rates were measured in subsequent observations. The experimental data confirmed that the mortality values of *S. granarius*, the primary pest, recorded under the same treatments were higher than for *C. ferrugineus* and *T. castaneum*. It is concluded that eliminating the primary pest species in the crop with shorter exposure to UV-C radiation may prevent the introduction of other crop pests that enter later. In the absence of the damage gate being opened by

S. granarius on the seed, secondary pests (*C. ferrugineus, T. castaneum*) cannot penetrate the seed (Nayak and Daglish 2018).

Modarres Najafabadi *et al.* (2014) confirmed that ultraviolet radiation can reduce egg laying, activating reproduction and reducing population growth rates of treated *Callosobruchus maculatus* (Fabricius) (Col.: Chrysomelidae). Ultraviolet-C (UV) radiation enhances oxidative stress within an insect's body as pointed out by Khan *et al.* 2022. Their results showed that after 3, 6, 12 and 24 h of UV-C exposure, the activity of SOD (superoxide dismutase) and CAT (catalase) of *Plutella xylostella* L. increased, while the activity of PPO (polyphenol oxidase), POD (peroxidase), AChE (acetylcholinesterase), CarE (carboxylesterase) and ACP (acid phosphatase) decreased with increasing exposure time. In summary, it affects the physiology and gene expression levels of *P. xylostella* in a destructive way.

The results of the analysis of the effects of UV irradiation on treated seeds can be controversial. According to Tertyshnaya *et al.* (2017), this physical exposure has no demonstrable effect on seed germination of the examined wheat varieties, but the biometric characteristics of developing plants were significantly altered.

Semenon *et al.* (2021) found that ultraviolet-C radiation positively affects seed quality and photosynthetic pigment content of plant leaves developing from treated seeds.

In contrast, Musil *et al.* (1998) found that UV radiation slowed seed germination. This depression increased with increased UV exposure and was most pronounced with shorter UV-B wavelengths. Glutathione reductase (GR) activity was also increased in seeds exposed to shorter UV-B wavelengths. Nevertheless, pigment analyses and enzyme activity assays demonstrated that UV-B irradiance did not affect the composition of photosynthetic pigments (chlorophylls and carotenoids) and the activity of antioxidant enzymes (superoxide dismutase and glutathione reductase) (Kim *et al.* 2004).

Our experimental results confirmed that using UV-C radiation in crop protection is a practical, non-chemical technique. However, this pest elimination technique is primarily recommended in environments exempt from viable stored seeds because the intactness of treated seeds cannot be clearly confirmed.

In this study, the effects of UV-C irradiation exposure on the mortality of stored product pests with different ecological functions (primary and secondary pests) and on the viability of treated maize and wheat seed were examined. Our results confirmed the insecticidal efficacy and the sensitivity of different pest species with specific ecological functions to UV-C irradiation. The primary stored product pest species in the crop with shorter exposure may prevent the colonization of secondary stored product pests and facultative predator stored product pests that enter later. The physiological deterioration of wheat and maize seeds by UV-C treatment cannot be clearly excluded. The tetrazolium test showed that wheat seeds were more sensitive to this physical stress than maize seeds under similar conditions.

Few effective plant alternative, non-chemical protection technologies are available today to successfully control stored product pests. The ionizing ultraviolet radiation we tested was undoubtedly an effective and promising option for future postharvest management of stored cereals. The treatment of UV-C radiation can be a useful, chemical-free solution for killing stored crop pests. Due to the low penetration rate, the method can be most successfully used against individuals moving on the surface (Andersen *et al.* 2006). Thus, it can be highly effective in combination with methods that expel insects from inside the crop, such as atmospheric heating or infrared radiation (Tungjitwitayakul *et al.* 2016; Keszthelyi *et al.* 2021; Mir *et al.* 2023). When using it, special attention must be paid to the regulations regarding human health, as direct UV-C radiation can cause eye irritation and possibly blindness (Zaffina *et al.* 2012). Based on our results, we believe that in a crop-free environment directly irradiating the pest can be an effective dynamic and environmentally friendly method, but its safe use still requires technical improvements. Future use of the application should be preceded by further environmental studies (such as mapping managed batches of crops and other non-target organisms), including the exact method of removal and expulsion of the pest from the crop (developing practical handling equipment and exploring its application, etc.).

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Competing interests

The authors declare no potential conflict of interest regarding the study reported in this paper.

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