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ORIGINAL ARTICLE

Assessment of some physical measures as safe and environmentally friendly alternative control agents for some common coleopteran insects in stored wheat products

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Abstract

Presently, finding effective, simple, inexpensive, hygienic and safe pest control agents are the biggest challenges in management of stored product insects, where those features are available in most physical factors. The insecticidal efficiency of four diversified physical control agents (ultraviolet and microwave irradiations, thermal remediation and silica nanoparticles) were assayed against the most common coleopteran insect species (*Sitophilus oryzae* L. and *Tribolium castaneum* Herbst) on stored wheat. Exposing tested insects to microwave irradiations (2450 MHz) for 25 sec gave preventive efficiency for stored material, which reached 97.68 and 99.02%, respectively. Sufficient exposure periods to kill 50% of the coleopteran adults ($LT_{50\%}$) were 13 and 14 sec, respectively. For effective control with UV radiations, *S. oryzae* should be exposed for 12 h and *T. castaneum* for 24 h. An exposure period of 24 h caused progeny reduction 95.24 and 89.72% and gave preventive efficiency of 94.25 and 93.37%, respectively. Values of $LT_{50\%}$ were 56.76 and 74.04 h, respectively. Exposing infested samples of the tested species to 70°C for 10 min killed 100% of adults and caused complete cessation of egg laying. Furthermore, 65°C or 70°C caused full progeny reduction. The lowest level of stored product weight loss (1.15 and 1.35%, respectively) occurred at 70°C, where sufficient exposure temperatures to kill 50% of the coleopteran adults ($LTD_{50\%}$) were 60.95°C and 61.63°C, respectively. Synthetic silica nanoparticles (SSiNPs) were more toxic against the tested populations than bio-silica nanoparticles (BSiNPs) after 48–72 h. A concentration of 1.00 $g \cdot kg^{-1}$ of tested silica nanoparticles caused significant reduction in adult populations, saved wheat grain vitality and gave least lost weights of flour (3.35–6.85%).

Key words: microwave, nanosilica, *Sitophilus oryzae*, temperature, *Tribolium castaneum*, ultraviolet irradiation

Introduction

Wheat is one of the world's most important staple grain products. Healthy wheat grains should undergo successful storage from the field to the consumer. Protecting stored grains from insect attack is important since most stored-grain pest insects are able to increase their population within a very short time and can destroy most stored grains especially during long-term storage (Pimentel 1991). Estimated annual losses of cereal grains due to insects and rodents are 30% in Africa and Asia (Hill 1990). Species of coleopteran insects in stored products have been researched more than other species. Red flour beetles *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) and rice weevils *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae) are considered to be the major insect pests in storage (Daglish *et al.* 1996; Campbell and Runnion 2003). Most coleopteran studies on stored products focus on these two species (Campolo *et al.* 2018).

Although the numbers of pesticides currently approved to protect stored grains are very limited and are chemical synthetics, such as methyl bromide and phosphine, they are commonly used worldwide as effective methods to control storage insects. Heavy and widespread use of chemical insecticides has resulted in negative effects on human public health, with serious environmental consequences such as depleting the earth's ozone layer (Leesch *et al.* 2000) and the occurrence of insecticide-resistant insect strains (Zhao *et al.* 2007). The above-mentioned reasons challenge researchers to find new, effective, hygienic, readily available, affordable and viable approaches to control stored product insect pests (Fields 2006; Mahdi and Rahman 2008; Collins and Kitchingman 2010) that are more environmentally friendly than synthetic chemicals.

Physical control involves physically changing the environment to make it hostile or inaccessible to insect pests. The physical environment of storage (temperature, relative humidity or grain moisture content and relative composition of atmospheric gases) or applying physical treatments (mechanical processing, physical removal, barriers, inert dusts, electric discharge, light, sound and ionizing irradiation) can be manipulated as hygienic physical control agents to manage insect pests in stored grain (Abd El-Aziz 2011).

There are many advantages of using physical agents in stored product insect control such as stored food products without toxic or undesirable chemical residues, no resistance development of pest insects, saving nutritive value, avoiding physicochemical changes of the treated products and inexpensive applications (Lapidot *et al.* 1991; Ahmed 2001; Zhao *et al.* 2007).

Using high-frequency electromagnetic energy in agriculture and pest control has been researched and reviewed by several authors (Highland and Wilson 1981; Moy 1993; Nelson 1996; Fields and Muir 1996). Microwaves are nonionizing irradiation that lack sufficient electromagnetic energy (Nelson 1967). Microwave radiation involved frequencies of more than 500 MHz with application frequencies of 869, 915, and 2450 MHz (Nelson 1996). Although, microwave radiation can kill pests existing inside or outside grain kernels (Halverson *et al.* 1999) with high penetrability, it does not have any harmful or severe impact on foodstuffs (Warchalewski *et al.* 2000; Vadivambal *et al.* 2007). A frequency of 2450 MHz can kill eggs and adults of *Tribolium confusum* (Halverson *et al.* 1996; Vadivambal *et al.* 2008; Vadivambal *et al.* 2010), *S. oryzae* (Zaho *et al.* 2007) and other insect species such as *Plodia interpunctella* (Shayesteh and Barthakur 1996; Vadivambal *et al.* 2010), eggs and pupae of *Delia radicum* (Biron *et al.* 1996), maize weevil *Sitophilus zeamais* (Motschulsky), *S. granarium* (Vadivambal 2009), *S. zeamais* (Hassan *et al.* 2010) and pulse beetle *Callosobruchus chinensis* (L.) (Bedi and Singh 1992; Singh *et al.* 2012). In these species it caused deformed adults, missing legs, or decreased reproduction rates (Nelson 1996). The principle behind killing insects using microwaves is the dielectric heating of insects which depends on its electrical properties (Novotny *et al.* 2013).

Ultraviolet radiations (UV-rays) (UV-C) have been used in many experimental studies such as embryological and physiological studies (Bodenstein 1953). It was widely used in pest control applications, for instance, germicide, insect attractant traps (Bruce 1975), and superficial elimination of insect eggs (Guerra *et al.* 1968). As a result, ultraviolet is a less penetrating radiation than other ionizing radiations, and it is used only with bulk grains or with small amounts (Hasan and Khan 1998). Many authors have examined UV radiation effects on the development of stored product insects (Calderon *et al.* 1985; Faruki 2005). Increasing exposure time to UV-rays caused a significant reduction in egg hatchability and adult eclosion of *T. castaneum*, *T. confusum* (Duval) and *Cadra cautella* (Walker) (Lepidoptera; Pyralidae) (Faruki *et al.* 2007).

Insects are poikilotherm organisms whose development and survival are affected easily by the surrounding temperature of the environment or microenvironment. In recent decades, high temperatures have been used extensively to manage storage insects with various methods such as radio frequencies, hot air, fluidized beds and microwave (Fields 1992; Nelson 1996; Roesli *et al.* 2003; Beckett *et al.* 2007; Kljajić and Andrić 2010). For effective and successful thermal control, the thermal tolerance of the host must be sufficiently lower than that of the target pest (Nelson 1967). High temperatures clearly affect physiological and biochemical aspects of storage insects (Fields 1992; Neven 2000) as well as survival (Beckett *et al.* 1998) or development of their different stages (Fields 1992; Beckett *et al.* 1998; Wright *et al.* 2002; Mahroof *et al.* 2003b; Loganathan *et al.* 2011). Many authors have discussed conventional heat treatment for disinfestation of stored grains from insects (Dosland *et al.* 2006; Phillips and Throne 2010; Alice *et al.* 2013). A temperature of 50°C has been suggested to be the most effective temperature to manage *T. castaneum* (Mahroof *et al.* 2003a; Campolo *et al.* 2013), *S. oryzae* (Golić *et al.* 2011; Campolo *et al.* 2013) and other insect species (Roesli *et al.* 2003).

Inert dusts (sands and other soil components, diatomaceous earth, silica aerogel, non-silica dusts and particle films such as kaolin and bentonite clays) are physical agents that have been used for centuries by Africans to control insects of stored grains (Fields and Muir 1996). Inert dusts are non-toxic to both humans and animals and can provide stored grains with continuous protection from insect infestations and save wheat quality (Abd El-Aziz 2011). Silica, which plugs up respiratory stomata of insects, can be used for controlling insect pests under field or laboratory

conditions (El-Samahy and Galal 2012; El-Samahy *et al.* 2014). Over the last 10 years nanotechnology has been incorporated into agriculture and crop protection as an innovative tool for pest control (Bhattacharyya *et al.* 2010; Khot *et al.* 2012; Cicek and Nadaroglu 2015; Kitherian 2017). Nanoparticles of silica are more active than their bulk counterpart because of their increased surface to volume ratio (Vani and Brindhaa 2013). Nanosilica or amorphous silica nanoparticles (SNP) have been used successfully to control a wide range of agricultural insect pests, ectoparasites of animals (Ulrichs *et al.* 2005) and stored product insects such as *S. oryzae*, *T. castaneum* and *Rhizopertha dominica* (F.) on wheat grains (El-Samahy *et al.* 2015). It caused more than 90% mortality for *S. oryzae* (Debnath *et al.* 2011) and 100% mortality for *Corcyra cephalonica* (S.) (Vani and Brindhaa 2013).

The current study was aimed to examine insecticidal efficiency of various, common, simple, inexpensive and safe physical control agents (ultraviolet rays, microwaves, high temperatures and silica nanoparticles) against Egyptian strains of *S. oryzae* and *T. castaneum* in stored wheat products.

Materials and Methods

Target insect species and grain samples

Adult samples of Egyptian strains of rice weevil, *S. oryzae* and the rust red flour beetle, *T. castaneum* were picked from local stores of El-Behera Governorate, established and maintained in the laboratory of Stored Product Pests Department, Plant Protection Research Institute, Agricultural Research Center, Sabahia, Alexandria, Egypt under constant conditions: 26 ± 2°C, 65 ± 5% RH (relative humidity) and a 12 : 12 light : dark photoperiod, without exposure to insecticides. Wheat grains or wheat flour, mixed with yeast (10 : 1 w/w), were used as rearing media for target insects, respectively. Healthy adults of the tested species were picked 2 weeks after emergence and subjected to further bioassay tests. Untreated, clean, sterilized grains and flour of wheat *Triticum vulgare* variety (Giza171) were obtained from Etay El-Baroud, Agriculture Research Station, El-Behera Governorate, Egypt.

Preparing insects for bioassay

Jars of 250 ml were mounted with 20 gm of the obtained wheat grains or wheat flour. Twenty sexed individuals (sex ratio 1 : 1) of *S. oryzae* adults were transferred to hard wheat jars, while 20 unsexed adults of *T. castaneum* beetles were transferred to jars of wheat flour. Each treatment and control were replicated six times in the case *S. oryzae*; or three times for *T. castaneum*.

Preparation of physical treatments for bioassay

Microwave treatments

The replicates of examined insect specimens were exposed to radiations of microwave energy using a household microwave system (LG Co. Korea – Model No: MS-2816 Mz). The power output of the generator was adjusted to 1,200 W and 2450 MHz. The samples were exposed for 5, 10, 15, 20 or 25 sec. The exposure period was determined using a stopwatch. Samples were investigated after 1 h, and mortality of adults was recorded.

UV-irradiation treatments

A wooden box (50 × 40 × 15 cm), and a mobile base was designed. At a height of 12 cm from the base, it was supplemented with an 8 W UV germicidal lamp (T5 8 GL) that emitted irradiation at a wavelength of 254 nm (Faruki *et al.* 2007). The effects of UV-radiation were evaluated at different exposure periods (3, 6, 12 and 24 h). At the end of the exposure period the UV-lamp was turned off and the samples were removed immediately. Then, all treated samples were kept under standard rearing conditions, and mortality of adults was recorded 1 day later.

Thermal treatments

Tested samples were subjected to high temperatures using a Torre Picenardi Oven (Model: Panacea 430) made in Italy (V: 220, 50/60Hz, A: 3.7, W: 800). The samples were exposed to five temperatures (50, 55, 60, 65 and 70°C) for 10 min. They were then removed immediately, and kept under standard rearing conditions. Mortality of adults was recorded 1 day later.

Silica nanoparticle applications

To evaluate the efficacy of silica nanoparticles (SiNPs) against both tested insects, two different sources of SiNPs were examined. The first source of SiNPs was obtained from rice husks (RHs) and named "bio-silica" (BSiNPs), while the second source was synthetic silica (SSiNPs) according to Kotoky and Dolui (2004) with 99.99% purity obtained from Nanotech Egypt Company Limited, Cairo. A transmission electronic microscope (TEM) was used to examine the shape and size of bio and synthetic silica nanoparticles as shown in Figure 1. The two nanoparticles were almost spherical and ranged in size from 10.95 to 23.90 nm for BSiNPs and 13.12–18.81 nm for SSiNPs. Effects of the SiNPs on 2 week old adults of both tested insect species were determined by contact toxicity assay at four rates: 0.25, 0.50, 1.00 and 1.50 g of SiNPs · kg^{-1} of wheat or flour. After application, samples were kept under standard rearing conditions and adult mortality was checked after 1, 2, and 3 days. Medium lethal concentration (LC_{50}) was estimated.

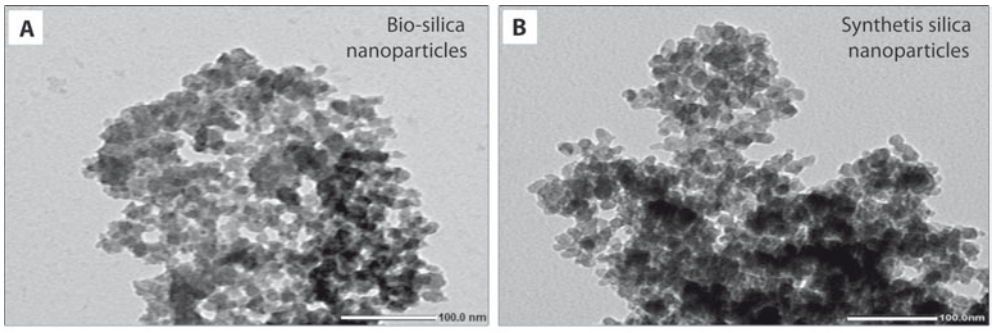

Fig. 1. Electron micrographs for silica nanoparticles. A – TEM image of bio-silica nanoparticles (BSiNPs), B – TEM image of synthetic silica nanoparticles (SSiNPs)

Estimating and calculating biological aspects

After 10 days of the above-mentioned treatment, egg laying numbers of surviving *S. oryzae* adults were recorded daily according to Frankenfeld (1948) and Howe (1952). After 6 weeks of treatment, egg hatchability percentages (emergence) of both tested insects were calculated according to the following equation of Moumouni *et al.* (2015):

$$\text{Emergence (\%)} = E/G \times 100,$$

where: E – of emerged adults, G – no. of laid eggs. Infestation reduction percentage was also calculated according to the following equation of Aldryhim (1990):

$$\text{Reduction (\%)} = EC - ET/EC \times 100,$$

where: EC – mean number of emerged adults in control, ET – mean number of emerged adults in treatment.

After 3 months, grain or flour weight losses were calculated according to the following equation of Ahmadi *et al.* (2009):

$$\text{Loss (\%)} = (W_1 - W_2) \times 100/W_1,$$

where: W_1 – weight of the sample before treatment, W_2 – weight of the sample after treatment. Then the efficiency percentage of each treatment was calculated according to the following equation of Mohamed *et al.* (2009):

$$E\ (\%) = (LC - LT) \times 100/LC,$$

where: LC – grain or flour weight losses in the control, LT – grain or flour weight losses in treatment.

Vitality of tested grain was also determined by applying the germination test according to Qi and Burkholder (1981). Germination of seeds was recorded 4 days after planting and germination percentages were calculated according to the following equation:

$$\%\,\text{Germination} = \frac{\text{Number of germinated grains}}{\text{Total number of planted grains}} \times 100.$$

Data analysis

Values of medium lethal exposure time (LT_{50}) for microwave and UV-irradiation treatments, medium lethal temperature (LTD_{50}) of thermal treatments and medium lethal concentration (LC_{50}) of SiNPs treatments were estimated by using Log dose Probit software (LdP) Line (Ehabsoft, Cairo, Egypt) according to Finney (1971). All obtained data of adult mortality, laid eggs, adult emergence, sample weight loss and seed germination were subjected to one-way analysis of variance (ANOVA) and means were compared by Duncan multiple range test at 5% probability level (Steel and Torrie 1980). The SPSS statistical software (Version 12) was used.

Results and Discussion

Effects of microwave radiations

Adult mortality, numbers of laid eggs and egg hatchability of *S. oryzae* adults treated with microwave for 5, 10, 15, 20 and 25 sec are presented in Table 1. Although exposing adults to microwave for 5 sec did not cause any significant difference in adult mortality and weight loss of wheat grain percentage as well as the control, it saved the vitality of stored wheat grains (91.65%). In contrast, the former case caused significant depletion in egg laying and adult emergence in comparison to the control. The mortality was significantly increased while egg laying and emerged adults were decreased with increased microwave exposure periods. In the case of exposing the adults for 25 sec, full mortality and complete cessation of egg laying were observed, achieving the highest level of insect pest population reduction (100%). Exposing adults to microwave for 25 sec gave preventive efficiency for stored wheat grains which reached 97.68%. The weight loss of wheat grain was not more than 1.67%. To kill 50% of adults ($LT_{50\%}$) (upper limit – lower limit) exposure for 12.99 (11.97–14.03) sec was sufficient.

Table 1. Impact of microwaves on biological aspects of *Sitophilus oryzae* adults and seed vitality, and their expected preventive efficiency for stored wheat grains at different exposure periods

Exposure periods [sec]	Mortality of adults [%]	Mean no. of laid eggs ±SE	Mean no. of emerged adults ±SE	Emergence [%]	Reduction [%]	Weight loss of wheat grain [%]	Efficiency [%]	Germination [%]
Control (0)	0.00 ± 0.00 e	183.33 ± 1.45 a	150.33 ± 0.88 a	82.00	00.00	71.17 ± 0.12 e	–	100.00 ± 0.00 a
5	6.65 ± 0.88 e	175.67 ± 1.20 b	142.00 ± 1.15 b	80.67	5.54	70.83 ± 0.15 e	00.42 ± 0.15 a	91.65 ± 0.33 a
10	33.35 ± 0.33 d	100.67 ± 1.45 c	63.00 ± 1.15 c	62.58	58.09	59.83 ± 0.15 d	15.88 ± 0.15 b	78.35 ± 0.88 b
15	56.65 ± 0.88 c	90.33 ± 0.88 d	50.33 ± 1.45 d	56.00	66.52	35.17 ± 0.15 c	50.60 ± 0.15 c	70.00 ± 0.58 b
20	75.00 ± 1.15 b	23.00 ± 1.00 e	9.67 ± 0.88 e	42.33	93.57	20.83 ± 0.12 b	70.70 ± 0.12 d	56.65 ± 0.88 c
25	88.35 ± 0.67 a	00.00 ± 0.00 f	00.00 ± 0.00 f	00.00	100.00	1.67 ± 0.09 a	97.68 ± 0.09 e	21.65 ± 0.88 d

Values are mean ± standard error; n = 6; column values followed by different letter(s) are significantly different at 0.05 levels

Table 2. Impact of microwaves on biological aspects of *Tribolium castaneum* adults and their expected preventive efficiency for stored wheat flour at different exposure periods

Exposure periods [sec]	Mortality of adults [%]	Mean no. of emerged adults [±SE]	Reduction [%]	Weight loss of wheat flour [%]	Efficiency [%]
Control (0)	0.00 ± 0.00 e	129.00 ± 1.53 a	00.00	66.35 ± 0.09 f	–
5	5.00 ± 0.58 e	112.33 ± 1.45 b	12.92	64.85 ± 0.09 e	2.26 ± 0.09 a
10	31.65 ± 0.88 d	77.33 ± 1.45 c	40.05	55.65 ± 0.09 d	16.13 ± 0.09 b
15	53.35 ± 1.20 c	37.33 ± 1.45 d	71.06	33.85 ± 0.12 c	48.98 ± 0.12 c
20	70.00 ± 1.00 b	12.67 ± 1.45 e	90.18	24.85 ± 0.09 b	62.55 ± 0.09 d
25	83.35 ± 0.33 a	00.00 ± 0.00 f	100.00	00.65 ± 0.03 a	99.02 ± 0.03 e

Values are mean ± standard error; n = 3; column values followed by different letter(s) are significantly different at 0.05 levels

In the case of *T. castaneum* adult treatments, it was shown that exposing adults to microwave irradiation for 5 sec did not cause any significant difference in adult mortality as well as in the control, but it significantly decreased percentages of stored flour weight loss and progeny production (Table 2). All microwave exposure periods significantly decreased the emerged adults compared to the control. No progeny emerged on wheat flour that was microwaved for 25 sec. To kill 50% of *T. castaneum* adults ($LT_{50\%}$) exposure for 13.95 (12.85–15.11) sec was sufficient. Moreover, exposing adults to microwave for 25 sec protected 99.02% of treated wheat flour.

Many researchers are interested in using microwave treatment as an alternative to chemical fumigation in pest control of post-harvest pests on agricultural products such as wheat (Shayesteh and Barthakur 1996), sorghum (More *et al.* 1992), rice (Xiong *et al.* 2004) and some food materials such as cherries (Ikediala *et al.* 1999) because of its high penetrability and safety. Microwave irradiation has obvious effects on some biological aspects of insects such as reduction of reproductive rates, malformation and body weight loss (Nelson 1996).

The obtained results agree with the results of Halverson *et al.* (1996), who found that the high power of microwave and source operating at a frequency less than 2.45 GHz gave mortality percentages of more than 93% for *S. zeamais* and other insects of stored products. Exposure to microwave energy not only kills the insects but also can cause physical injuries and reduced reproduction rates in surviving insects (Nelson 1996). Earlier studies showed that eradication of insects increased with increasing microwave energy, while the seed viability, germination capacity, and seedling vigor decreased (Campana *et al.* 1993; Bhaskara-Reddy 1998). Singh *et al.* (2012) also concluded that germination capacity and seed viability of chickpea, pigeon pea, and green gram were affected by microwave exposure periods and power level.

Complete mortality of all life stages of *T. castaneum* can occur by using a power level of 400 W and an exposure time of 56 sec or at 500 W for 28 sec. Increasing power levels or exposure periods or both can significantly increase mortality. Germination of barley seeds was decreased with an increase in power level or longer exposure periods (Vadivambal *et al.* 2008). Complete mortality was achieved for adults of *T. castaneum*

and *Oryzaephilus surinamensis* (L.) insects and larvae of *T. castaneum* when the power was 800 W and the exposure time was 30 or 40 sec. Mortality of *T. castaneum* larvae was also 100% when the power and exposure period were 600 W and 40 sec, respectively (Manickavasagan *et al.* 2013). The medium lethal time (LT_{50}) of exposure to microwave irradiation indicated that the adult stage of *S. zeamais* was more tolerant to microwave irradiation than the other developmental stages (Tungjitwitayakul *et al.* 2016). An output of 840 watt power and an exposure period of 50 sec caused the highest mortality (90%) of *T. castaneum* and khapra beetle *Trogoderma granarium* Everts. Mortality increased with increasing concentrations or exposure periods or both (Agha *et al.* 2017). It was evident that increasing power and exposure periods significantly increased the mortality of the Mediterranean Flour Moth *Ephestia kuehniella* Zeller (Azizoglu *et al.* 2011), which may be caused by water present in the body fluid (Shayesteh and Barthakur 1996).

Effects of UV-radiations

Obtained data (Table 3) showed that the mortality of *S. oryzae* adults increased with longer ultraviolet exposure periods. For effective control with UV radiations, infested samples should be exposed for at least 12 h since there were no significant differences between adult mortality of treated samples for 3 or 6 h and untreated samples at $p < 0.05$ (LSD < 0.05 = 1.88). All UV exposure periods caused significant reductions in the number of laid eggs and emerged adults in comparison to the control. An exposure period of 24 h decreased an adult emergence percentage to 17.67%. Moreover, treated samples with UV for 24 h was sufficient to give preventive efficiency up to 94.25% and weight loss of stored wheat did not increase than 2.30%. UV radiation for 24 h didn't have any significant negative effects on vitality of stored wheat grains. To kill 50% of adults ($LT_{50\%}$) an exposure period of 56.76 (35.5–145.29) h was sufficient.

The impacts of UV-radiation exposure periods on levels of infestations with *T. castaneum* are given in Table 4. Exposing the adults to UV-radiations for 12 h did not cause any significant mortality in comparison to the control or shorter exposure periods. The numbers of emerged adults were significantly decreased with increasing the exposure period. All of the ultraviolet exposure periods significantly reduced weight loss of wheat flour in comparison to the control at $p < 0.05$ (LSD < 0.05 = 0.23). Infested samples should be exposed to UV-irradiation for a period of not less than

Table 3. Impact of UV-radiation on biological aspects of *Sitophilus oryzae* adults and seed vitality, and their expected preventive efficiency for stored wheat grains at different exposure periods

Exposure periods [h]	Mortality of adults [%]	Mean no. of laid eggs [±SE]	Mean no. of emerged adults [±SE]	Emergence [%]	Reduction [%]	Weight loss [%]	Efficiency [%]	Germination [%]
Control	00.00 ± 0.00 b	78.00 ± 1.53 a	63.00 ± 1.15 a	80.67	00.00	40.00 ± 0.12 d	–	100.00 ± 0.00 a
3	1.65 ± 0.33 b	67.67 ± 1.2 b	51.33 ± 1.86 b	76.00	18.52	38.00 ± 0.15 d	5.00 ± 0.15 a	93.35 ± 0.88 ab
6	8.35 ± 0.33 b	50.67 ± 1.2 c	30.33 ± 0.88 c	59.67	51.86	28.30 ± 0.12 c	29.25 ± 0.12 b	95.00 ± 0.58 ab
12	18.35 ± 0.88 a	35.33 ± 1.45 d	14.67 ± 1.45 d	41.51	76.71	22.30 ± 0.15 b	44.25 ± 0.15 c	88.35 ± 0.67 b
24	26.65 ± 0.88 a	16.67 ± 0.88 e	3.00 ± 0.58 e	17.67	95.24	2.30 ± 0.03 a	94.25 ± 0.03 d	88.35 ± 0.88 b

Values are mean ± standard error; n = 6; column values followed by different letter(s) are significantly different at 0.05 levels

Table 4. Impact of UV-radiation on biological aspects of *Tribolium castaneun* adults and their expected preventive efficiency for stored wheat flour at different exposure periods

Exposure periods [h]	Mortality of adults [%]	Mean no. of emerged adults [±SE]	Reduction [%]	Weight loss of wheat flour [%]	Efficiency [%]
Control	0.00 ± 0.00 c	71.33 ± 2.03 a	0.00	34.70 ± 0.09 e	–
3	1.65 ± 0.33 c	55.33 ± 1.45 b	22.43	30.30 ± 0.09 d	12.68 ± 0.09 a
6	6.65 ± 0.33 cb	36.33 ± 1.76 c	49.07	23.70 ± 0.15 c	31.70 ± 0.15 b
12	13.35 ± 0.88 b	24.67 ± 1.86 d	65.41	18.30 ± 0.09 b	47.26 ± 0.09 c
24	23.35 ± 0.88 a	7.33 ± 1.20 e	89.72	2.30 ± 0.09 a	93.37 ± 0.09 d

Values are mean ± standard error; n = 3; column values followed by different letter(s) are significantly different at 0.05 levels

24 h to obtain the highest mortality of adults (23.35%) and progeny reduction (89.72%) that could save 93.37% of wheat flour. To kill 50% of adults ($LT_{50\%}$) an exposure time of 74.04 (42.07–256.54) h was sufficient.

The effects of UV-rays were reported by Sharma and Dwivedi (1997) who found that UV-rays inhibited oviposition and emergence of *C. chinensis*. Earlier, Guerra *et al.* (1968) reported that UV-radiations of a short wavelength (2537A°) could completely inhibit egg hatchability of *Heliothis virescens* (Fabricius) and *H. zea* (Boddie). Percentages of egg hatchability were gradually decreased with increasing periods of exposure and eggs were completely killed after an exposure period of 20 min. Knipling (1970) suggested that ionizing radiation could be used to control economically important insects that cause chromosomal translocations and then fertility reduction. Irradiation of late-stage larvae of Indian meal moth, *Plodia interpunctella* with UV-rays caused inhibition of adult emergence (Beard 1972). UV-rays can be used to suppress the population of insects (Calderon *et al.* 1985). Irradiation of *Exorista sorbillans* pupae with UV-rays significantly reduced adult emergence and caused deformation of larvae and adults (Hasan *et al.* 1998).

UV-exposure of larvae (Faruki *et al.* 2005) and pupae of *A. diaperinus* (Parween 2004) significantly reduced reproduction. When Faruki (2005) exposed larvae of *T. castaneum* to UV-rays, he noticed that adult emergence was significantly decreased. Moreover, egg-hatching and adult emergence were significantly reduced in *T. castaneum*, *T. confusum* and *Cadra cautelladue* when eggs were exposed to UV-rays (Faruki *et al.* 2007). The mortality of *S. oryzae* was highest when ultraviolet radiation was 254 nm for 20 min. The combination of ultraviolet radiation and Chinese wingnut oils gave the best control and mortality rates which reached 100% after 4–5 days of treatment (Zhihua and Yin 2007). Finally, exposing adults of astigmatid mites, *Tyrophagus putrescentiae* (Schrank, 1781) to UV-C (260 nm) and UV-B (315 nm) and exposure periods ranging from 3 to 15 min, caused mortality rates between 85–100% for UV-C and 62–83% for UV-B (Bakr 2013).

Effects of thermal remediation

The results of exposing *S. oryzae* adults and stored wheat grains to different thermal treatments with ascending temperatures are presented in Table 5. It is clear that the mortality of *S. oryzae* was increased with increasing temperatures. To obtain significant mortality, adults should be exposed to 60°C for at least 10 min. Exposing adults to 70°C for 10 min killed 100% of adults and caused complete cessation of egg laying. Treating adults at 50°C did not cause any significant reduction of laid eggs, while exposing adults to 55°C or more could cause significant reduction of laid eggs. No adult emergence was noticed at 65°C or more, so it was considered to be the optimal temperature for full progeny reduction (*PR* %). Thermal remediation had a significant negative effect on adult emergence; however it did not have any significant effect on wheat grain vitality. At 70°C the lowest level of wheat grain weight loss (1.15%) and the highest level of preventative efficiency (98.48%) were observed. To kill 50% of adults ($LTD_{50\%}$) exposure at 60.95°C (60.29–61.63) was efffective.

Impacts of thermal remediation on adult mortality, progeny production, adult emergence reduction of *T. castaneum* and weight loss of wheat flour are presented in Table 6. No significant difference was detected for adult mortality between treatments of 50 or 55°C and the control. Complete mortality of an examined population was achieved when samples were

Table 5. Impact of thermal treatment on biological aspects of *Sitophilus oryzae* adults and seed vitality, and their expected preventive efficiency for stored wheat grains

Temperature [°C]	Mortality of adults [%]	Mean no. of laid eggs [±SE]	Mean no. of emerged adults [±SE]	Emergence [%]	Reduction [%]	Weight loss [%]	Efficiency [%]	Germination [%]
Control	00.00 ± 0.00 d	117.67 ± 1.20 a	92.00 ± 1.53 a	78.18	00.00	76.00 ± 0.15 f	–	100.00 ± 0.00 a
50	3.35 ± 0.67 d	116.00 ± 1.00 a	72.67 ± 1.45 b	62.65	21.01	64.65 ± 0.18 e	14.93 ± 0.18	100.00 ± 0.00 a
55	5.00 ± 0.58 d	96.33 ± 1.76 b	58.00 ± 1.53 c	60.21	36.96	52.65 ± 0.15 d	30.72 ± 0.15	96.65 ± 0.33 a
60	40.00 ± 1.15 c	75.33 ± 1.45 c	31.67 ± 1.76 d	42.04	65.58	44.00 ± 0.12 c	42.11 ± 0.12	95.00 ± 0.58 a
65	85.00 ± 1.00 b	17.00 ± 1.73 d	00.00 ± 0.00 e	00.00	100.00	8.65 ± 0.23 b	88.62 ± 0.23	100.00 ± 0.00 a
70	100.00 ± 0.00 a	00.00 ± 0.00 e	00.00 ± 0.00 e	00.00	100.00	1.15 ± 0.03 a	98.49 ± 0.03	100.00 ± 0.00 a

Values are mean ± standard error; n = 6; column values followed by different letter(s) are significantly different at 0.05 levels

Table 6. Impact of thermal treatment on biological aspects of *Tribolium castaneum* adults and their expected preventive efficiency for stored wheat flour

Temperature [°C]	Mortality of adults [%]	Mean no. of emerged adults [±SE]	Reduction [%]	Weight loss of wheat flour [%]	Efficiency [%]
Control	00.00 ± 0.00 d	95.33 ± 1.45 a	00.00	70.85 ± 0.12 f	–
50	1.65 ± 0.33 d	78.00 ± 1.00 b	18.18	60.15 ± 0.09 e	15.10 ± 0.09 a
55	3.35 ± 0.33 d	67.67 ± 1.45 c	29.02	51.00 ± 0.15 d	28.02 ± 0.15 b
60	38.35 ± 0.88 c	43.33 ± 1.76 d	54.55	45.65 ± 0.09 c	35.57 ± 0.09 c
65	76.65 ± 0.88 b	0.00 ± 0.00 e	100.00	6.65 ± 0.20 b	90.61 ± 0.20 d
70	100.00 ± 0.00 a	0.00 ± 0.00 e	100.00	1.35 ± 0.07 a	98.09 ± 0.07 e

Values are mean ± standard error; n = 3; column values followed by different letter(s) are significantly different at 0.05 levels

exposed to 70°C for 10 min. It was clear that the numbers of emerged adults were significantly decreased in treatments compared to the control. At 65 and 70°C the highest level of progeny reduction (100%) was achieved, while 50°C achieved the lowest. Temperatures of 65 or 70°C were sufficient to protect approximately 93.35 and 98.65% of wheat flour from *T. castaneum* infestation, respectively. Exposure temperature, sufficient to kill 50% of adults ($LTD_{50\%}$) was 61.63°C (60.92–62.39).

It is clear that insect pest manipulation with extreme temperatures provides a useful tool for the control of *S. oryzae* and *T. castaneum* in an Integrated Pest Management Program. Insects die when exposed to high temperatures because of their limited physiological capacity to thermoregulate (Fields 1992). Rapid mortality of insects exposed to high temperatures may be due to increased respiration and metabolic rates (Adler *et al.* 2000; Mbata and Phillips 2001). For most stored product insects, 25 to 33°C is considered to be optimal for development. Moreover, from 13 to 25°C or from 33 to 35°C, insects can develop completely and produce offspring. At less than 13°C or higher than 35°C, stored product insects will die. Lethal temperatures will vary depending on the species and life stage of the insect (Fields 1992; Ali *et al.* 1997). Increasing temperatures significantly increased egg mortality rate. One hundred percent mortality was achieved after 180, 120, 60, 40 and 30 sec at temperatures of 54, 60, 65, 70 and 75°C, respectively. Mortality is generally due to physiological and biochemical changes (Neven 2000).

There is a wide variation between species in their ability to survive at high temperature (Strang 1992). Coleopteran species of insects have different susceptibilities to high temperature treatment (49°C). Here, the survival of different species is arranged ascendingly (*O. surinamensis* or *T. confusum*), (*O. mercator* or *Cathartus quadricollis*), (*Gibbium psylloides* or *S. granarium*), (*Trogoderma variable*, *T. castaneum* or *S. oryzae*), (*R. dominica* or *C. pusillus*) then *Lasioderma serricorne* (Kirkpatrick and Tilton 1972). In the current study increasing temperatures had significant effects on adult mortality, which agrees with Baker *et al.* (1956) who detected that a temperature of 70.4°C was lethal to *T. confusum* and *S. granaries* after 1 week of exposure, and a temperature of 80.6°C for 18 sec was also lethal to 100% of *T. confusum* larvae. Only 2–3% of *T. castaneum* and *Rhyzopertha dominica* (F.) adults survived at 57°C for 32 sec (Fields 1992; Fields and Muir 1996). Young larvae of *T. castaneum* were tolerant to temperatures over 50°C while exposure to 50°C for 72 h caused 99% mortality. Moreover, temperature had a negative impact on progeny production of *T. castaneum* adults (Mahroof *et al.* 2003b). Exposing all developmental stages of *T. castaneum* and *T. confusum* and adults of *T. castaneum, S. oryzae* and *R. dominica* to 51°C and 50°C, respectively, for less than 2 h could cause 100% mortality (Arthur 2000; Tilley *et al.* 2007). Temperatures of 54 and 55°C and an exposure time of 0.06 h were sufficient to kill 90% of young larvae of *S. paniceum*, whereas increasing exposure time to 1.3, 0.63 and 0.25 h, killed 99% of *T. castaneum*, *L. serricorne* and *T. confusum*, respectively (Abdelghany *et al.* 2010).

Exposing adults of *S. oryzae* to 70°C for 10 min was very effective and 100% mortality was achieved. These results agree with Zewar (1993) who found that 70°C for 20 min gave complete mortality for *S. granaries* adults. Eggs laid on wheat grains tolerate higher temperature better than adults and needed 70°C for 15 min to inhibit the emergence of adults. In addition, emergence of *T. castaneum* decreased with increased temperature and exposure time (Boina and Subramanyam 2004). When exposing pupae and adults of *T. castaneum* to 50°C for 39 and 60 min, respectively, there was a significant reduction in oviposition, survival of developmental stages, and progeny production (Mahroof *et al.* 2005).

It is evident from the present study that high temperatures provided adequate protection for stored products against infestation by *S. oryzae* and *T. castaneum*. It offers a great prospect for successful protection of

stored material against attack by the mentioned insects for small and medium storage and does not require any extra financial expenses. In the present study temperature did not have any significant effect on the vitality of wheat grains which is in agreement with Murdock and Shade (1991) who found that the temperatures and exposure times necessary to disinfest the cowpeas did not have a significant effect on cooking time and germination of cowpea seeds. But it does not agree with the findings of Purohit *et al.* (2013) who observed that the germination of treated mung bean seeds was reduced significantly due to microwave exposure and increasing temperature and exposure times.

Physical toxicity of silica nanoparticles

Adult mortality of exposed *S. oryzae* and *T. castaneum* to different concentrations of synthetic or bio silica nanoparticles is shown in Table 7, where the mortality was dependent on concentrations and duration of exposure. Mortality of the two tested coleopteran insect species increased with increasing concentrations and exposure periods. Toxic responses of the two tested insects to silica nanoparticles were similar. After 48–72 h of exposure, synthetic silica nanoparticles (SSiNPs) were more toxic than bio-silica nanoparticles (BSiNPs) against *S. oryzae*. Treatment of 1 kg of infested wheat grains with 0.86 g of SSiNPs was sufficient to kill 50% of exposed adults in less than 72 h. On the other hand, no significant differences were observed between entomotoxicity of SSiNPs and BSiNPs against *T. castaneum* adults until 48 h of exposure. Even though the entomotoxic effect of the tested silica nanoparticles increased significantly after 72 h, the toxicity of SSiNPs against *T. castaneum* was higher than BSiNPs by approximately 4.34 fold.

Biological changes of *S. oryzae* and *T. castaneum,* resulting from silica nanoparticle application, are presented in Tables 8 and 9, respectively. It was obvious that exposing adults to different concentrations (0.25, 0.50, 1.00 and 1.50 g · kg^{-1}) of silica nanoparticles caused significant reduction in the numbers of eggs laid by the tested insects, however, no significant differences were detected between examined sources of silica nanoparticles. Observed numbers of eggs laid by *S. oryzae* adults exposed to 0.25 or 0.50 g of SSiNPs were significantly less than when BSiNPs were used. No significant difference was detected between the toxicity values of the tested silica nanoparticles in higher concentrations (1.00 or 1.50 g · kg^{-1}), which caused a significant reduction of egg laying. Numbers of emerged adults of *S. oryzae* or *T. castaneum* were completely frustrated especially in higher concentrations of both tested materials. Concentrations of 1.00 g · kg^{-1} or more caused significant reductions in the adult populations of both species, and reached 100%. The least weight loss of wheat grains (2.35–4.35%) was observed when adults of *S. oryzae* were exposed to SSiNPs concentrations of 1.00 g or more, or BSiNPs with a concentration of 1.5 g for kg wheat gains. Both tested silica nanoparticles saved wheat grain vitality and then seed germination. On the other hand, the least losses of flour weight (3.35–6.85%) were observed in samples treated with 1.00 g or more of SSiNPs or BSiNPs.

Amorphous silica is the active component of the diatomaceous earth dusts that are classified as desiccant dusts and are recognized as „safe products". It was approved by the US Food and Drug Administration and it is harmless for humans and mammals (Subramanyam *et al.* 1994; Erb-Brinkmann 2000). The recommended application rate for diatomaceous earth dusts is dependent on the source or origin of the dust, species of stored grain insect and exposure conditions (Erb-Brinkmann and Straube 2002; Stathers *et al.* 2002). An inert dust, based on silica, has been used as a stored grain protectant (Owolade *et al.* 2008). The nanoparticles exhibit unique properties compared to

Table 7. Physical toxicity of silica nanoparticles against newly emerged adults of *Sitophylus oryzae* and *Tribolium castaneum* after different exposure periods

Target insect	Exposure periods [h]	Silica nanoparticles treatments									
		Synthetic (SSiNPs)					Bio (BSiNPs)				
		LC_{50} [g · kg^{-1}]	confidence limits lower	confidence limits upper	slope value (± SE)	χ^2	LC_{50} [g · kg^{-1}]	confidence limits lower	confidence limits upper	slope value (± SE)	χ^2
S. oryzae	24	1.65	1.20	3.06	1.17 ± 0.23	3.11	6.26	2.54	270.94	0.75 ± 0.24	1.35
	48	0.86	0.65	1.24	1.06 ± 0.22	2.62	2.43	1.34	22.95	0.69 ± 0.22	1.87
	72	0.23	0.13	0.31	1.30 ± 0.23	1.31	0.86	0.63	1.35	0.92 ± 0.22	4.57
T. castaneum	24	2.15	1.53	4.15	1.36 ± 0.25	4.23	5.33	2.49	61.88	0.89 ± 0.25	1.95
	48	1.28	0.94	2.26	1.04 ± 0.22	1.93	3.46	1.85	23.17	0.86 ± 0.23	1.80
	72	0.29	0.16	0.40	1.12 ± 0.22	0.50	1.26	0.93	2.17	1.06 ± 0.22	3.79

LC_{50} – concentration [g · kg^{-1}] that causes 50% of adult mortality; SE – standard error; χ^2 – Chi-square value

Table 8. Physical toxicity of silica nanoparticles against newly emerged adults of *Sitophilus oryzae* and *Tribolium castaneum* after different exposure periods

Silica nanoparticles treatment	Concentration [g · kg^{-1}]	No. of laid eggs	No. of emerged adults	Emergence [%]	Loss of wheat [%]	Reduction [%]	Germination [%]
Synthetic (SSiNPs)	0.25	67.67 ± 1.45 c	36.67 ± 2.03 c	54.00 ± 0.02 b	37.85 ± 0.23 e	56.35	100.00 ± 0.00 a
	0.50	38.33 ± 1.20 e	6.67 ± 0.88 f	17.00 ± 0.01 c	17.50 ± 0.12 c	92.06	95.00 ± 0.58 b
	1.00	20.33 ± 1.45 f	0.00 ± 0.00 e	0.00 ± 0.00 d	3.15 ± 0.27 a	100.00	95.00 ± 0.00 b
	1.50	7.00 ± 1.15 g	0.00 ± 0.00 e	0.00 ± 0.00 d	2.35 ± 0.09 a	100.00	96.65 ± 0.33 ab
Bio (BSiNPs)	0.25	72.00 ± 1.53 b	40.67 ± 1.76 b	56.00 ± 0.01 b	40.65 ± 0.12 f	51.58	96.65 ± 0.33 ab
	0.50	42.67 ± 0.88 d	9.00 ± 1.73 d	21.00 ± 0.04 c	19.85 ± 0.09 d	89.29	95.00 ± 0.00 b
	1.00	24.33 ± 1.45 f	0.00 ± 0.00 e	0.00 ± 0.00 d	7.35 ± 0.09 b	100.00	98.35 ± 0.33 ab
	1.50	8.33 ± 1.45 g	0.00 ± 0.00 e	0.00 ± 0.00 d	4.35 ± 0.09 a	100.00	96.65 ± 0.33 ab
Control	0.00	101.67 ± 1.76 a	84.00 ± 2.08 a	83.00 ± 0.03 a	56.50 ± 0.12 g		100.00 ± 0.00 a

Values are mean ± standard error; n = 6; column values followed by different letter(s) are significantly different at 0.05 levels

Table 9. Effects of ascending concentrations of synthetic and bio-silica nanoparticles on adult emergence of *Tribolium castaneum* adults and associated flour weight loss

Silica nanoparticles treatment	Concentration [g · kg^{-1}]	No. of emerged adults	Adult no. reduction [%]	Flour weight loss [%]
Synthetic (SSiNPs)	0.25	40.67 ± 1.45 c	42.72	33.65 ± 0.15 f
	0.50	7.00 ± 1.73 e	90.14	14.50 ± 0.12 d
	1.00	0.00 ± 0.00 f	100.00	5.15 ± 0.03 bc
	1.50	0.00 ± 0.00 f	100.00	3.35 ± 0.09 a
Bio (BSiNPs)	0.25	44.67 ± 1.76 b	37.08	36.35 ± 0.15 g
	0.50	12.00 ± 1.53 d	83.10	16.85 ± 0.15 e
	1.00	0.00 ± 0.00 f	100.00	6.85 ± 0.09 c
	1.50	0.00 ± 0.00 f	100.00	4.00 ± 0.15 ab
Control	0.00	71.00 ± 2.08 a		49.15 ± 0.12 h

Values are mean ± standard error; n = 3; column values followed by different letter(s) are significantly different at 0.05 levels

their bulk material, including higher toxicity (Anjali *et al.* 2010). Nanosilica may be useful against stored grain insects, animal parasites, household pests, worms, fungal organisms, etc. (Ghormade *et al.* 2011). The toxicity of SiO_2 and Al_2O_3 nanoparticles is due to their binding to the insect cuticle, followed by physical sorption of waxes and lipids, leading to insect dehydration (Benelli 2018). SiNPs have high mobility, enabling better penetration into insect tissues by direct contact through the insect's cuticle, or by ingestion and penetration through the digestive tract (Margulis-Gosh and Magdassi 2012). They have been used in insect pest management as molecule delivery, release control improvement and toxic material (Cáceres *et al.* 2019).

Exposing adult *S. oryzae* and *T. confusum* to different diatomaceous earth formulations (Silicosec, Biofa GmbH, Germany) at four dose rates: 0.25, 0.5, 1 and 1.5 g · kg^{-1}, showed that *T. confusu*m was less susceptible to SilicoSec than *S. oryzae*. In general, the rates of 1 and 1.5 g · kg^{-1} of wheat provided a satisfactory level of protection against the two examined species. Mortality was higher at longer exposure intervals (Athanassiou *et al.* 2005). *Tribolium castaneum* was more susceptible to hydrophobic synthetic amorphous silica (SAS) powder. When exposing *S. oryzae* adults, no significant difference was detected between LT_{95} values of hydrophobic and hydrophilic SAS (Li *et al.* 2020). Silica nanoparticles were found to be highly effective against *S. oryzae* which caused mortality rates of more than 90%, indicating the effectiveness of SiNPs as a stored product insect pest control agent (Debnath *et al.* 2011). Silicon dioxide nanoparticles could also be applied to protect stored grains against adults of *R. dominica* and *T. confusum* at low concentrations (Ziaee and Ganji 2016). It has the ability to prevent development of progeny and reduce the emergence of adults of the F1 generation, when parents and progeny of *S. oryzae* or both are treated; no new progeny was found in rice treated

with SiNPs even after 2 months of treatment (Debnath *et al.* 2011). Zinc oxide nanoparticles (ZnO NPs) and hydrophilic silica nanoparticles (SiO_2 NPs) exhibited a significant toxic effect against *S. oryzae* and *C. maculatus* while *T. castaneum* showed high resistance against the two tested materials at the highest concentrations (0.3, 2 and 8 $g \cdot kg^{-1}$ of SNPs), which caused adult mortality percentages of 81.6, 98.3 and 58.3%, respectively. Moreover, they caused high reductions in F1-progeny (%) with *C. maculatus* and *S. oryzae* (Haroun *et al.* 2020).

Silica nanoparticles can also kill larvae of *Spodoptera litura*, so they can be considered to be nanocides and an alternative to commercial insecticides, with physical action (Debnath *et al.* 2012). In addition, hydrophobic nanosilica at 112.5 ppm was effective against some mosquito species. Hydrophobic nanosilica had high larvicidal and pupicidal effects against *Anopheles stephensi*, *Aedes aegypti* and *Culex quinquefasciatus* (Barik *et al.* 2012). Finally, application of nanosilica as dust spray had higher significant entomotoxic effects against larvae of *Plutella xylostella* than larva dipping, leaf dipping, or solution spray. Mortality rate increased with increasing time exposure and concentration. It reached 58 and 85% at 24 and 72 h after treatment, respectively, with an application rate of 1 $mg \cdot cm^{-2}$ (Shoaib *et al.* 2018).

References

Abd El-Aziz S.E. 2011. Control strategies of stored product pests. Journal of Entomology 8: 101–122. DOI: 10.3923/je.2011.101.122

Abdelghany A.Y., Awadalla S.S., Abdel-Baky N.F., El-Syrafi H.A., Fields P.G. 2010. Effect of high and low temperatures on the drugstore beetle (Coleoptera: Anobiidae). Journal of Economic Entomology 103: 1909–1914. DOI: 10.1603/EC10054

Adler C., Corinth H.G., Reichmuth C. 2000. Modified atmospheres. p. 105–146. In: "Alternatives to Pesticides in Stored Product" (B. Subramanyam, D.W. Hagstrum, eds.). IPM. Kluwer, Boston, MA, USA.

Agha W.N.A., Amin A.H., Khidr S.K., Ismail A.Y. 2017. Entomocidal activity of microwave energy and some aqueous plant extracts against *Tribolium castaneum* Herbst and *Trogoderma granarium* Everts. p. 020005-1–020005-13. In: AIP Conference Proceedings 1888 for the 6th International Conference and Workshops on Basic and Applied Sciences, Erbil, Iraq, 18–19 March 2017. DOI: https://doi.org/10.1063/1.5004282

Ahmadi H., Fathollahzadeh H., Mobli H. 2009. Post-harvest physical and mechanical properties of apricot fruits, pits and kernels (cv Sonnati Salmas) cultivated in Iran. Pakistan Journal of Nutrition 8: 264–268. DOI: 10.3923/pjn.2009.264.268

Ahmed M. 2001. Disinfestations of stored grains pulses dried fruits and nuts and other dried foods. p. 77–112. In: "Food Irradiation: Principles and Applications" (R.A. Molins, ed.). John Wiley & Sons, Inc., New York, USA.

Aldryhim Y.N. 1990. Efficacy of the amorphous silica dust, Dryacide, against *Tribolium confusum* Duv. and *Sitophilus granarius* (L.) (Coleoptera: Tenebrionidae and Curculionidae). Journal of Stored Product Research 26 (4): 207–210. DOI: https://doi.org/10.1016/0022-474X(90)90023-L

Ali M.F., Abdel-Reheem E.F.M., Abdel-Rahman H.A. 1997. Effect of temperature extremes on the survival and biology of the carpet beetle, *Attagenus fasciatus* (Thunberg) (Coleoptera: Dermestidae). Journal of Stored Products Research 33: 147–156. DOI: https://doi.org/10.1016/S0022-474X(96)00044-6

Alice J., Sujeetha R.P., Srikanth N. 2013. Effect of hot and cold treatments for the management of Pulse beetle *Callosobruchus maculatus* (Fab) in pulses. IOSR Journal of Agriculture and Veterinary Science 3 (3): 29–33.

Anjali C.H., Khan S.S., Margulis-Goshen K., Magdassi S., Mukherjee A., Chandrasekaran N. 2010. Formulation of water-dispersible nanopermethrin for larvicida applications. Ecotoxicology and Environmental Safety 73 (8): 1932–1936. DOI: 10.1016/j.ecoenv.2010.08.039

Arthur F.H. 2000. Toxicity of diatomaceous earth to red flour beetles and confused flour beetles (Coleoptera: Tenebrionidae): effect of temperature and relative humidity. Journal of Economic Entomology 93: 526–532. DOI: 10.1603/0022-0493-93.2.526

Athanassiou C.G., Vayias B.J., Dimizasa C.B., Kavallieratosb N.G., Papagregoriouc A.S. Buchelosa C.T. 2005. Insecticidal efficacy of diatomaceous earth against *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae) and *Tribolium confusum* du Val (Coleoptera: Tenebrionidae) on stored wheat: influence of dose rate, temperature and exposure interval. Journal of Stored Products Research 41 (1): 47–55. DOI: https://doi.org/10.1016/j.jspr.2003.12.001

Azizoglu U., Yılmaz S., Karaborklu S., Ayvaz A. 2011. Ovicidal activity of microwave and UV radiations on mediterranean flour moth *Ephestia kuehniella* Zeller, 1879 (Lepidoptera: Pyralidae). Turkiye Entomoloji Dergisi 35 (1): 437–446.

Baker V.H., Wiant D.E., Taboada O. 1956. Some effects of microwaves on certain insects which infest wheat and flour. Journal of Economic Entomology 49: 33–37. DOI: https://doi.org/10.1093/jee/49.1.33

Bakr A.A. 2013. Effectiveness of ultraviolet radiation as a physical method in controlling the stored product mite, *Tyrophagus putrescentiae* (Acari: Acaridae). Journal of Entomology 10 (1): 43–48. DOI: 10.3923/je.2013.43.48

Barik T.K., Kamaraju R., Gowswami A. 2012. Silica nanoparticle: a potential new insecticide for mosquito vector control. Parasitol Research 111 (3): 1075–1083. DOI: 10.1007/s00436-012-2934-6. Epub 2012.

Beard R.L. 1972. Lethal action of UV irradiation on insects. Journal of Economic Entomology 65: 650–654. DOI: https://doi.org/10.1093/jee/65.3.650

Beckett S.J., Fields P.G., Subramanyam B. 2007. Disinfestation of stored products and associated structures using heat. p. 182–237. In: "Heat Treatments for Postharvest Pest Control: Theory and Practice" (J. Tang, E. Mitcham, S. Wang, S. Lurie, eds.). CAB International, Cambridge, MA, USA. DOI: 10.1079/9781845932527.0182

Beckett S.J., Morton R., Darby J.A. 1998. The mortality of *Rhyzopertha dominica* (F.) (Coleoptera: Bostrychidae) and *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae) at moderate temperatures. Journal of Stored Products Research 34: 363–376. DOI: 10.1016/S0022-474X(98)00022-8

Bedi S.S., Singh M. 1992. Microwaves for control of stored grain insects. National Academy of Science Letter 15 (6): 195–197.

Benelli G. 2018. Mode of action of nanoparticles against insects. Environmental Science and Pollution Research 25: 12329–12341. DOI: 10.1007/s11356-018-1850-4

Bhaskara-Reddy M.V., Raghavan G.S.V., Kushalappa A.C., Paulitz T.C. 1998. Effect of microwave treatment on quality of wheat seeds infected with *Fusarium graminearum*. Journal of Agricultural Engineering Research 71 (2): 113–117. DOI: https://doi.org/10.1006/jaer.1998.0305

Bhattacharyya A., Bhaumik A., Rani P.U., Mandal S., Epidi T.T. 2010. Nano-particles – A recent approach to insect pest control. African Journal of Biotechnology 9: 3489–3493. DOI: https://www.ajol.info/index.php/ajb/article/view/82345

Biron D., Vincent C., Giroux M., Maire A. 1996. Lethal effects of microwave exposures on eggs and pupae of the cabbage maggot and cabbage plants. Journal of Microwave Power and Electromagnetic Energy 31 (4): 228–237. DOI: https://doi.org/10.1080/08327823.1996.11688314

Bodenstein D. 1953. Embryonic development. p. 780–822. In: "Insect Physiology "(K.D. Roder, ed.). John Wiley, USA.

Boina D., Subramanyam B. 2004. Relative susceptibility of *Tribolium confusum* life stages exposed to elevated temperatures. Journal of Economic Entomology 97 (6): 2168–2173. DOI: https://doi.org/10.1093/jee/97.6.2168

Bruce W.A. 1975. Effect of UV-radiation on egg hatch of *Plodia interpunctella* (Lepidoptera: Pyralidae). Journal of Stored Products Research 11 (3–4): 243–244. DOI: https://doi.org/10.1016/0022-474X(75)90038-7

Cáceres M., Vassena C.V., Garcerá M.D., Santo-Orihuela P.L. 2019. Silica nanoparticles for insect pest control. Current Pharmaceutical Design 25 (37): 4030–4038. DOI: 10.2174/1381612825666191015152855

Calderon M., Bruce W.A., Leesch L.G. 1985. Effect of UV-radiation on eggs of *Tribolium castaneum*. Phytoparasitica 13: 179–244.

Campana L.E., Sempe M.E., Filgueira R.R. 1993. Physical, chemical and baking properties of wheat dried with microwave energy. Cereal Chemistry 70 (6): 760–762.

Campbell J.F., Runnion C. 2003 Patch exploitation by female red Xour beetles, *Tribolium castaneum*. Journal of Insect Science 3 (20): 8.

Campolo O., Verdone M., Laudani F., Malacrinò A. 2013. Response of four stored products insects to a structural heat treatment in a flour mill. Journal of Stored Products Research 54: 54–58. DOI: 10.1016/j.jspr.2013.05.001

Campolo O., Giunti G., Russo A., Palmeri V., Zappalà L. 2018. Essential oils in stored product insect pest control. Journal of Food Quality 2018: 1–18. DOI: https://doi.org/10.1155/2018/6906105

Cicek S., Nadaroglu H. 2015. The use of nanotechnology in the agriculture. Advances in Nano Research 3: 207–223. DOI: http://dx.doi.org/10.12989/anr.2015.3.4.207

Collins D.A., Kitchingman L. 2010. The effect of ultraviolet C radiation on stored-product pests. 10th International Working Conference on Stored Product Protection. Julius-Kühn-Archiv 425: 632–636. DOI: 10.5073/jka.2010.425.153

Daglish G.J., Eelkema M., Harrison L.M. 1996. Control of *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae) in paddy rice using chloropyrifos-methyl or fenintrothion in combination with several other protectants. Journal of Stored Products Research 32: 247–253. DOI: https://doi.org/10.1016/S0022-474X(96)00013-6

Debnath N., Mitraa S., Dasa S., Goswamia A. 2012. Synthesis of surface functionalized silica nanoparticles and their use as entomotoxic nanocides. Powder Technology 221: 252–256. DOI: https://doi.org/10.1016/j.powtec.2012.01.009

Debnath N., Das S., Seth D., Chandra R., Bhattacharya S.Ch., Goswami A. 2011. Entomotoxic effect of silica nanoparticles against *Sitophilus oryzae* (L.). Journal of Pest Science 84: 99–105. DOI: https://doi.org/10.1007/s10340-010-0332-3

Dosland O., Subramanyam B., Sheppard K., Mahroof R. 2006. Temperature modification for insect control. p. 89–103. In: "Insect Management for Food Storage and Processing" (J. Heaps, ed.). American Association for Cereal Chemistry, St. Paul, MN, USA. DOI: 10.1016/B978-1-891127-46-5.50015-5

El-Samahy M.F.M., Galal O.A. 2012. Evaluation of silica nanoparticles as a new approach to control faba bean (*Vicia faba* L.) insects and its genotoxic effect on M2 plants. Egyptian Journal of Agricultural Research 90 (2): 869–888.

El-Samahy M.F.M., El-Ghobary A.M.A., Khafagy I.F. 2014. Using silica nanoparticles and neem oil as new approaches to control *Tula absoluta* (Meyrick) in tomato under field conditions. International Journal of Plant and Soil Science 3 (10): 1355–1365. DOI: 10.9734/IJPSS/2014/8435

El-Samahy M.F.M., Hamza A.M.M., El-Ghobary A.M.A. 2015. A new silica nanoparticles formulation as stored product protectant. Egyptian Journal of Plant Protection Research 3 (2): 88–103.

Erb-Brinkmann M. 2000. Application of amorphous silica dust (SilicoSec) in Germany: practical experiences. Integrated Protection of Stored Products, IOBC Bulletin 23: 239–242.

Erb-Brinkmann M., Straube B. 2002. Stored products protection with amorphous silica dust (SilicoSec) in Germany: practical experiences and laboratory trials. Integrated Protection of Stored Products, IOBC Bulletin 25: 220–227.

Faruki S.I. 2005. Effects of UV-radiation on the growth and development of malathion-susceptible and multi-resistant strains of *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). Bangladesh Journal of Entomology 25 (2): 55–63.

Faruki S.I. Das D.R., Khatun S. 2005. Effects of UV-radiation on the larvae of the lesser mealworm, *Alphitobius diaperinus* (Panzer) (Coleoptera: Tenebrionidae) and their progeny. Journal of Biological Sciences 5 (4): 444–448. DOI: 10.3923/jbs.2005.444.448

Faruki S.I., Das D.R., Khan A.R., Khatun M. 2007. Effects of ultraviolet (254 nm) irradiation on egg hatching and adult emergence of the flour beetles, *Tribolium castaneum*, *T. confusum* and the almond moth, *Cadra cautella*. Journal of Insect Science 7: 36. DOI: 10.1673/031.007.3601

Fields P.G. 2006. Effect of *Pisum sativum* fractions on the mortality and progeny production of nine stored grain beetles. Journal of Stored Products Research 42: 86–96. https://doi.org/10.1016/j.jspr.2004.11.005

Fields P.G. 1992. The control of stored-product insects and mites with extreme temperatures. Journal of Stored Products Research 28: 89–118. DOI: https://doi.org/10.1016/0022-474-X(92)90018-L

Fields P.G., Muir W.E. 1996. Physical Control, in Integrated Management of Insects in Stored Products. Marcel Dekker, Inc., New York, USA.

Finney D.J. 1971. Probit Analysis. 3rd ed. Cambridge University Press, Cambridge. DOI: https://doi.org/10.1002/jps.2600600940

Frankenfeld J.C. 1948. Staining methods for detecting weevil infestation in grains. USDA. Bureau of Entomology and Plant Quarantine 4: 256.

Ghormade V., Deshpande M.V., Paknikar K.M. 2011. Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnology Advances 29 (6): 792–803. DOI: 10.1016/j.biotechadv.2011.06.007

Golić M.P., Andrić G., Kljajić P. 2011. Effects of 50°C temperature on *Sitophilus granarius* (L.), *Sitophilus oryzae* (L.) and *Sitophilus zeamais* (Motsch.). Pesticides and Phytomedicine 26 (3): 221–227. DOI: 10.2298/PIF1103221P

Guerra A.A., Ouye M.T., Bullock H.R. 1968. Effect of ultraviolet irradiation on egg hatch, subsequent larval development, and adult longevity of the tobacco budworm and the bollworm. Journal of Economic Entomology 61: 541–542. DOI: https://doi.org/10.1093/jee/61.2.541

Halverson S.L., Burkholder W.E., Bigelow T.S., Nordheim E.V., Misenheimer M.E. 1996. High-power microwave radiation as an alternative insect control method for stored-products. Journal of Economic Entomology 89 (6): 1638–1648. DOI: https://doi.org/10.1093/jee/89.6.1638

Halverson S.L., Phillips T.W., Bigelow T.S., Mbata G.N., Payton M.E. 1999. The control of various species of stored-product insects with EHF energy. p. 541–544. In: Proceedings of the Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions. San Diego, CA, 1 November, 1999.

Haroun S.A., Elnaggar M.E., Zein D.M., Gad R.I. 2020. Insecticidal efficiency and safety of zinc oxide and hydrophilic silica nanoparticles against some stored seed insects. Journal of Plant Protection Research 60 (1): 77–85. DOI: https://doi.org/10.24425/jppr.2020.132211

Hasan M., Khan A.R. 1998. Control of stored-product pests by irradiation. Integrated Pest Management Review 3: 15–29. DOI: https://doi.org/10.1023/A:1009621606024

Hasan M., Jahan M.S., Khan A.R. 1998. Effect of UV radiation on the Uzi-fly, *Exorista sorbillans* Widemann, an endoparasitiod of the silkworm, *Bombyx mori* L. International Journal of Tropical Insect Science 18 (1): 87–91. DOI: https://doi.org/10.1017/S1742758400007505

Hassan A., Horsten D.V., Lucke W. 2010. Application of microwave energy to control maize weevil (*Sitophilus zeamais*) in maize grains (*Zea mays*). World Food System – A Contribution from Europe, Tropentag, Zurich.

Highland H.A., Wilson R. 1981. Resistance of polymer films to penetration by lesser grain borer and description of a device for measuring resistance. Journal of Economic Entomology 74 (1): 67–70. DOI: https://doi.org/10.1093/jee/74.1.67

Hill D.S. 1990. Pests of Stored Products and their Control. CRC Press, Boca Raton, FL, USA, 274 pp.

Howe R.W. 1952. The biology of the rice weevil *Calandra oryzae*. Annals of Applied Biology 39 (2): 168–180. DOI: https://doi.org/10.1111/j.1744-7348.1952.tb00895.x

Ikediala J.N., Tang J., Neven L.G., Drake S.R. 1999. Quarantine treatment of cherries using 915 MHz microwaves: Temperature mapping, codling moth mortality, and fruit quality. Postharvest Biology and Technology 16 (2): 127–137. DOI: 10.1016/S0925-5214(99)00018-6

Khot L.R., Sankaran S., Maja J.M., Ehsani R., Schuster E.W. 2012. Applications of nanomaterials in agricultural production and crop protection: A review. Crop Protection 35: 64–70. DOI: 10.1016/j.cropro.2012.01.007

Kirkpatrick R.L., Tilton E.W. 1972. Infrared radiation to control adult stored-product Coleoptera. Journal Georgia Entomological Society 7: 73–75.

Kitherian S. 2017. Nano and bio-nanoparticles for insect control. Research Journal of Nanoscience and Nanotechnology 7: 1–9. DOI: 10.3923/rjnn.2017.1.9

Kljajić P., Andrić G. 2010. Physical measures for storage insects control. p. 168–182. In: Proceedings of the XIV International Symposium FEED Technology. Novi Sad, Serbia, 19–21 October 2010.

Knipling H.F. 1970. Suppression of pest Lepidoptera by releasing partially sterile males. A theoretical appraisal. Bioscience 20: 465–469. DOI: https://doi.org/10.2307/1295155

Kotoky T., Dolui S. 2004 Synthesis and characterisation of polyvinyl alcohol (PVA)/silica hybrid composites derived through the sol-gel method in aqueous medium: effect of acid content, silica content and viscosity of PVA on the dispersion characteristics of silica and the physical properties of the composites. Journal of Sol-Gel Science and Technology 29: 107–114. DOI: https://doi.org/10.1023/B:JSST.0000023011.15323.45

Lapidot M., Saveanu S., Padova R., Ross I. 1991. Insect disinfestations by irradiation, in insect disinfestation of food and agricultural products by irradiation. International Atomic Energy Agency (IAEA), Vienna, Austria, 103 pp.

Leesch J.G., Knapp G.F., Mackey B.E. 2000. Methyl bromide adsorption on activated carbon to control emissions from commodity fumigations. Journal of Stored Products Research 36 (1): 65–74. DOI: https://doi.org/10.1016/S0022-474X(99)00028-4

Li Y., Agarwal M., Caob Y., Rena Y. 2020. Effect of synthetic amorphous silica (SAS) powder on the cuticle of *Tribolium castaneum* and *Sitophilus oryzae* using hyperspectral imaging technique: Synthetic amorphous silica effect on *Tribolium castaneum* and *Sitophilus oryzae*. Pest Management Science 76 (1): 314–323. DOI: https://doi.org/10.1002/ps.5517

Loganathan M., Jayas D.S., Fields P.G., White N.D.G. 2011. Low and high temperatures for the control of cowpea beetle, *Callosobruchus maculatus* (F.) (Coleoptera : Bruchidae) in chickpeas. Journal of Stored Products Research 47 (3): 244–248. DOI: https://doi.org/10.1016/j.jspr.2011.03.005

Mahdi S.H.A., Rahman M.K. 2008. Insecticidal effect of some spices on *Callosobruchus maculatus* (Fabricius) in black gram seeds. University Journal of Zoology Rajshahi University 27: 47–50. DOI: 10.3329/ujzru.v27i0.1953

Mahroof R., Subramanyam B., Eustace D. 2003a. Temperature and relative humidity profiles during heat treatment of mills, and its efficacy against *Tribolium castaneum* (Herbst) life stages. Journal of Stored Products Research 39 (5): 555–569. DOI: https://doi.org/10.1016/S0022-474X(02)00062-0

Mahroof R., Subramanyam B., Throne J.E., Menon A. 2003b. Time-mortality relationships for *Tribolium castaneum* (Coleoptera: Tenebrionidae) life stages exposed to elevated temperatures. Journal of Economic Entomology 96: 1345–1351. DOI: https://doi.org/10.1093/jee/96.4.1345

Mahroof R., Subramanyam B., Flinn P. 2005. Reproductive performance of *Tribolium castaneum* (Coleoptera: Tenebrionidae) exposed to the minimum heat treatment temperature as pupae and adults. Journal of Economic Entomology 98: 626–633. DOI: https://doi.org/10.1093/jee/98.2.626

Manickavasagan A., Alahakoon P.M.K., Al-Busaidi T.K., Al-Adawi S., Wahaibi A.K.A, Al-Raeesi A.A., Al-Yahyai R., Jayas D.S. 2013. Disinfestation of stored dates using microwave energy. Journal of Stored Products Research 55: 1–5. DOI: https://doi.org/10.1016/j.jspr.2013.05

Margulis-Gosh K., Magdassi S. 2012. Nanotechnology: an advanced approach to the development of potent insecticides. p. 295–314. In: "Advanced Technologies for Managing Insect Pests" (I. Ishaaya, P.S. Reddy, H.A. Rami, eds.). Springer Science and Business Media, New York, USA.

Mbata G.N., Phillips T.W. 2001. Effect of temperature and exposure time on mortality of stored-product insects exposed to low pressure. Journal of Economic Entomology. 94 (5): 1302–1307. DOI: https://doi.org/10.1603/0022-0493-94.5.1302

Mohamed M.I.E., Abdelgaleil S.A.M., Abdel Rasoul M.A. 2009. Potential of essential oils to control *Sitophilus oryzae* (L.) and *Tribolium castaneum* (Herbst) on stored wheat. Alexandria Science Exchange Journal 30 (4): 419–426. DOI: 10.21608/asejaiqjsae.2009.3254

More H.G, Magan N., Stenning B.C. 1992. Effect of microwave heating on quality and mycoflora of sorghum grain. Journal of Stored Products Research 28 (4): 251–256. DOI: https://doi.org/10.1016/0022-474X(92)90005-B

Moumouni D.A., Doumma A., Seyni I.S. 2015. Effect of solar drying on the biological parameters of the cowpea weevil, *Callosobruchus maculatus* Fab. (Coleoptera-Bruchidae), in Sahelian area. Journal of Applied Biosciences 84 (1): 7723–7729. DOI: 10.4314/jab.v84i1.10

Moy J.H. 1993. Efficacy of irradiation vs thermal methods as quarantine treatments for tropical fruits. Radiation Physics and Chemistry 42: 269–272. DOI: https://doi.org/10.1016/0969-806X(93)90247-R

Murdock L.L., Shade R.E. 1991. Eradication of cowpea weevil (Coleoptera: Bruchidae) in cowpeas by solar heating. American Entomologist 37: 228–231. DOI: https://doi.org/10.1093/ae/37.4.228

Nelson S.O. 1996. Review and assessment of radio-frequency and microwave energy for stored-grain insect control. Transactions of the American Society of Agricultural Engineers 39 (4): 1475–1484. DOI: https://pubag.nal.usda.gov/catalog/34207

Nelson S.O. 1967. Electromagnetic energy. p. 89–145. In: "Pest Control Biological, Physical, and Selected Chemical

Methods" (W.W. Kilgore, R.L. Doutt, eds.). Academic Press, New York.

Neven L.G. 2000. Physiological responses of insects to heat. Postharvest Biology and Technology 21: 103–111. DOI: 10.1016/S0925-5214(00)00169-1

Novotny M., Jan S., Karel S., Vladimir T. 2013. Sterilization of biotic pests by microwave radiation. Procedia Engineering 57: 1094–1099. DOI: https://doi.org/10.1016/j.proeng.2013.04.138

Owolade O.F., Ogunleti D.O., Adenekan M.O. 2008. Titanium dioxide affects disease development and yield of edible cowpea. Journal of Plant Protection Research 48 (3): 329–335. DOI: 10.2478/v10045-008-0042-5

Parween S. 2004. Triflumuron: a potent candidate for the control of two strains of *Tribolium castaneum* Herbst (Coleopteran: Tenebrionidae). Journal of Biological Science 12: 7–14.

Phillips T.W., Throne J.E. 2010. Biorational approaches to manage stored product insects. Annual Review of Entomology 55: 375–397. DOI: 10.1146/annurev.ento.54.110807.090451

Pimentel D. 1991. World resource and food losses to pests. p. 5–11. In: "Ecology and Management of Food-industry Pests" (J.R. Gorham, ed.). AOAC, USA.

Purohit P., Jsyas D.S., Yadav B.K., Chelladurai V., Fields P.G., White N.D.G. 2013. Microwaves to control *Callosobruchus maculatus* in stored mung bean (*Vigna radiate*). Journal of Stored Products Research 53: 19–22. DOI: https://doi.org/10.1016/j.jspr.2013.01.002

Qi Y.T., Burkholder W. 1981. Protection of stored wheat from the granary weevil by vegetable oils. Journal of Economic Entomology 74: 502–505. DOI: https://doi.org/10.1093/jee/74.5.502

Roesli R., Subramanyam B., Fairchild F., Behnke K. 2003. Trap catches of stored-product insect numbers before and after heat treatment in a pilot feed mill. Journal of Stored Products Research 39 (2): 521–540. DOI: https://doi.org/10.1016/S0022-474X(02)00058-9

Sharma M.K., Dwivedi S.C. 1997. Investigation on the effects of ultra-violet and infra-red (IR) light on the life cycle of *Callosobruchus chinensis* linn. Journal of Advanced Zoology 18 (1): 27–31. DOI: https://www.cabi.org/isc/abstract/19981110074

Shayesteh N., Barthakur N.N. 1996. Mortality and behavior of two stored-product insect species during microwave irradiation. Journal of Stored Products Research 32 (3): 239–246. DOI: https://doi.org/10.1016/S0022-474X(96)00016-1

Shoaib A., Elabasy A., Waqas M., Lin L., Zhang X.Q., Shi Z. 2018. Entomotoxic effect of silicon dioxide nanoparticles on *Plutella. xylostella* (L.) (Lepidoptera: Plutellidae) under laboratory conditions. Toxicological and Environmental Chemistry 100 (4): 1–12 DOI: 10.1080/02772248.2017.1387786

Singh R., Singh K.K., Kotwaliwale N. 2012. Study on disinfestation of pulses using microwave technique. Journal of Food Science and Technology 49 (4): 505–509. DOI: 10.1007/s13197-011-0296-1

Stathers T.E., Chigariro J., Mudiwa M., Mvumi B.M., Golob P. 2002. Small-scale farmer perceptions of diatomaceous earth products as potential stored grain protectants in Zimbabwe. Crop Protection 21: 1049–1060. DOI: https://doi.org/10.1016/S0261-2194(02)00089-3

Steel R.G.D., Torrie J.H. 1980. Principles and Procedures of Statistics. 2nd ed. New York: McGraw-Hill, USA.

Strang T.J.K. 1992. A review of published temperatures for the control of pest insects in museums. Collection Forum 8: 41–67.

Subramanyam B., Swanson C.L., Madamanchi N., Norwood S. 1994. Effectiveness of insector, a new diatomaceous earth formulation, in suppressing several stored-grain insect species. p. 650–659. In: Proceedings of the 6th International. Conference on Stored-Product Protection, Canberra, Australia.

Tilley D.R., Casada M.E., Arthur F.H. 2007. Heat treatment for disinfestation of empty grain storage bins. Journal of Stored Products Research 43 (3): 221–228. DOI: 10.1016/j.jspr.2006.04.005

Tungjitwitayakul J., Tatun N., Vajarasathira B., Sakurai S. 2016. Effects of ultraviolet-C and microwave irradiation on the expression of heat shock protein genes in the maize weevil (Coleoptera: Curculionidae) European Journal of Entomology 113: 135–142. DOI: 10.14411/eje.2016.017

Ulrichs C., Mewis I., Goswami A. 2005. Crop diversification aiming nutritional security in West Bengal biotechnology of stinging capsules in nature's water-blooms. Annual Technology Issue of State Agriculture Technologists Service Association: 1–18.

Vadivambal R., Jayas D.S., White N.D.G. 2007. Wheat disinfestations using microwave energy. Journal of Stored Production Research 43 (4): 508–514. DOI: https://doi.org/10.1016/j.jspr.2007.01.007

Vadivambal R. 2009. Disinfestation of stored grain insects using microwave energy. Ph.D. thesis, University of Manitoba, Winnipeg, Canada.

Vadivambal R., Jayas D.S., White N.D.G. 2008. Determination of mortality of different life stages of *Tribolium castaneum* (Coleoptera: Tenebrionidae) in stored barley using microwaves. Journal of Economic Entomology 101 (3): 1011–1021. DOI: https://doi.org/10.1093/jee/101.3.1011

Vadivambal R., Deji O.F., Jayas D.S., White N.D.G. 2010. Disinfestation of stored corn using microwave energy. Agriculture and Biology Journal of North America 1 (1): 18–26.

Vani C., Brindhaa U. 2013. Silica nanoparticles as nanocides against *Corcyra cephalonica* (S.), the stored grain pest. International Journal of Pharma and Bio Sciences 4 (3): B1108–B1118.

Warchalewski J.R., Pradzynska A., Gralik J., Nawrot J. 2000. The effect of gamma and microwave irradiation of wheat grain on development parameters of some stored grain pests. Food/Nahrung 44 (6): 411–414. DOI: https://doi.org/10.1002/1521-3803(20001201)44:6<411::AID-FOOD411>3.0.CO;2-L

Wright E.J., Sinclair E.A., Annis P.C. 2002. Laboratory determination of the requirements for control of *Trogoderma variable* (Coleoptera: Dermestidae) by heat. Journal of Stored Products Research 38: 147–155. DOI: https://doi.org/10.1016/S0022-474X(01)00011-X

Xiong S.B., Liu Q.Y., Cheng X.X., Zhao S.M. 2004. Effect of microwave on rice mould growth properties. In: Proceedings of the CIGR International Conference (B. Wang, Q. Huang, Q. Li, Y. Chen, F. Mei, Q. Wei, J. Zhuo, eds.). China Agricultural Science and Technology, Beijing, 50 pp.

Zewar M.M. 1993. The use of high temperature for disinfesting wheat from *Sitophilus granarius* (L.) and cowpea *Callosobruchus maculatus* (F.). Egyptian Journal of Agricultural Research 71 (3): 671–678.

Zhao S., Qiu C., Xiong S., Cheng X. 2007. A thermal lethal model of rice weevils subjected to microwave irradiation. Journal of Stored Products Research 43 (4): 430–434. DOI: 10.1016/j.jspr.2006.12.005

Zhihua W.H.T.K.L., Yin L.H.J.W.G. 2007. Preliminary studies on effects of non-chemical treatments on *Sitophilus oryzae* adults. Grain Storage 2007: 05. DOI: http://en.cnki.com.cn/Article_en/CJFDTotal-LSCZ200705004.htm

Ziaee M., Ganji Z. 2016. Insecticidal efficacy of silica nanoparticles against *Rhyzopertha dominica* F. and *Tribolium confusum* Jacquelin du Val. Journal of Plant Protection Research 56 (3): 251–256. DOI: https://doi.org/10.1515/jppr-2016-0037