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Effectiveness of microwave radiation on life stages of *Sitotroga cerealella* and its impact on chemical composition of wheat grains

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Summary The efficacy of microwave power (MP) (110, 220, and 440 W) for five exposure times against different stages of *Sitotroga cerealella* was assessed. Mortality percentage of life stages, adult emergence, and chemical components in wheat grains were evaluated. Complete egg mortality (100%) was achieved with 440 W and an exposure time of 270 sec. Larvae and pupae were affected by increasing MP, resulting in a reduction in adult emergence. Furthermore, full mortality of adults increased with longer exposure periods to MP, reaching 100% 3 days after treatment with 110 W of MP and exposure times of 150, 210, and 270 sec. Complete adult mortality was achieved 2 days after treatment with 220 W and exposure times of 210 and 270 sec, and 1 day after treatment with 440 W and exposure times of 150, 210, and 270 sec. Moreover, MP caused a slight reduction in the chemical components of wheat grains except for fibre content. These findings suggest that MP may be a useful method for the management of *S. cerealella*.

Additional keywords: Adult mortality, angoumois grain moth, chemical components, heat grains, microwave

Introduction

Twenty percent of the world's protein and forty percent of its calories come from wheat (Kumar *et al.,* 2015). Furthermore, 35% of the world's population primarily consumes wheat as a food source. Consequently, wheat is cultivated more extensively than maize on a global scale (Breitkreuz *et al.,* 2020; Miedaner *et al.,* 2020). According to Bouchelos (2018), 17% of the food produced globally is believed to be damaged during storage due to insect infestations. Stored grains can be infested by several destructive insect pests, such as *Trogoderma granarium* Everts, *Sitophilus* spp., angoumois grain moth *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechiidae), and other insects (Cogburn and Bollich, 1980; França-Silva *et al.,* 2020; Stathas *et al.,* 2023).

Sitotoroga cerealella larvae infest various stored cereals, leading to significant damage to the grains in terms of weight and quality loss. If populations of this insect pest become substantial, they could potentially decimate grain stocks (Shafique *et al.,* 2006; Borzoui *et al.,* 2017). Management of this insect pest typically involves the use of chemical fumigants, but the widespread use of chemical insecticides poses serious risks to the ecosystem and to animal and human health (Hagstrum and Phillips, 2017). In accordance with insect management strategies, scientists in this field advocate for a significant reduction in the use of synthetic insecticides and the adoption of more environmentally friendly methods (Phillips and Throne, 2010; Lucchi and Benelli, 2018).

Microwaves are electromagnetic waves that fall within the electromagnetic spectrum between radio waves and infrared radiation. Their frequency ranges from 300 MHz to 300 GHz, which means their wavelength is between 1 and 1000 mm (Šuhajda, 2006). The transformation of electrical energy to microwave energy occurs within a generator which is composed of high-voltage tubes that produce microwave radiation. A portion of this radiation is reflected, some is absorbed, and some penetrates through. Heat is then generated from the absorbed microwave radiation (Novotny *et*

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al., 2013). The dielectric heating effect produced by grains, which are typically poor electrical conductors, forms the basis for using microwaves to kill insects. There is potential for selective heating of insects in grain due to the dependence of this heating on the material's electrical properties. The primary advantage of using microwave energy as a green control tool is that food does not contain any chemical residues, meaning there are no negative effects on humans or the environment (Taheri *et al.,* 2022).

Several reports have illustrated how microwave energy, when applied to stored products effectively combats a range of insect pests (El-Naggar and Mikhaiel, 2011; Das *et al.,* 2013; Manickavasagan *et al.,* 2013; Pandir and Guven, 2014; Sadeghi *et al.,* 2018; Patil *et al.,* 2020; Abed *et al.,* 2023). Furthermore, few reports studied effect of microwave on *S. cerealella* larvae such as García-Mosqueda *et al.* (2019). However, the effect of microwave powers on the mortality of life stages of *S. cerealella* and the biological aspects such as adult emergence from treated stages have not been studied before. Therefore, the current study focuses on examining the susceptibility of various *S. cerealella* stages to microwave powers (MP) as well as their latent effects on adult emergence from treated stages and their impact on the chemical components of stored wheat**.**

Materials and Methods

Rearing of *S. cerealella*

The culture of *S. cerealella* was initiated from eggs of a laboratory strain provided by the Plant Protection Institute of the Ministry of Agriculture in Giza, Egypt. The individuals of *S. cerealella* used in the study were obtained from the laboratory culture that had been raised in glass jars for several generations at a consistent temperature and relative humidity of 26°C and 65% r.h. Fresh egg masses were collected from the jars, and the neonate larvae were placed in glass jars containing sterilized wheat grain. The larvae reached adulthood, and the life cycle of *S. cerealella* was maintained on wheat grains as described by Akter *et al.* (2013). Different stages were used in this study, including newly laid eggs and one-day-old adults. Larvae and pupae were treated by exposing wheat grains to microwave powers (MP) for 21-23 days and 27-29 days.

Microwave energy treatment equipment

A Sharp model R-340 resistivity microwave oven was used, operating at 230-240V and 50Hz, with an input of 1.60 kilowatts and 7.2A output power of 1100 watts, a capacity of 33 liters, and cavity dimensions of 375 mm (width) x 226 mm (height) x 387 mm (diameter). The operating frequency of the oven was 2450 megahertz. The various life stages of wheat grains under investigation were exposed to different microwave powers of 110, 220, and 440 watts (10%, 20%, and 40% of the output power of 1100 watts).

Exposure of *S. cerealella* life stages to microwave powers (MP)

One day old *S. cerealella* eggs (100 eggs), fourth instar larvae (10 g of wheat grains containing larvae 21-23 days), 5 days old pupae (10 g of wheat grains containing pupae 27-29 days) and one day old adults (50 adults) were exposed to three MP levels, 110, 220, and 440 W for 30, 90, 150, 210, and 270 seconds (sec). The experiments were conducted in four replicates, with treated insects compared to untreated insects. Subsequently, treated immature stages (eggs, larvae, and pupae) were placed in glass jars with muslin cloth coverings (5 cm in diameter and 5 cm in depth) for incubation under the same conditions as in rearing. To determine the percentage of mortality after treatment, the jars were examined daily until a percentage of adult emergence was noted (since it can be difficult to find larvae or pupae inside the grains) (Abd El-Ghaffar *et al.,* 2016; Gad *et al.,* 2025a, b).

Major chemical components of wheat treated with microwave powers (MP)

The impact of MP on the chemical components of wheat was investigated using standard analytical methods. The MP treatment was in the 750–2500 nm wavelength range using a near-infrared (NIR) spectroscope (model DA1650 – FOSS Corporation – Denmark) (Gad *et al.,* 2021). The analyses were conducted on 20 grams of wheat grains, assessing the percentages of protein, fat, carbohydrates, moisture, fibre, and ash in both treated and untreated wheat.

Statistical analysis

The mortality data were analyzed using probit analysis (Finney, 1971) to determine the LT_{50} and LT_{90} values. Subsequently, the data underwent ANOVA analysis. Mean separations were computed using Tukey's HSD test at a significance threshold of less than 0.05. The statistical analysis was performed using SPSS 21.0 software (SPSS, Chicago, IL, USA).

Results

Treatment of eggs by MP and their latent effects

Our results show that as exposure time or microwave power (MP) increased, the percentage of treated eggs of *S. cerealella* that were killed also increased compared to the control group. Strong egg mortality rates of 93.6% and 99.7% were achieved with an exposure time of 270 sec and MP levels of 110 and 220 W, as shown in Figure 1. The LT_{50} values were 0.62 and 131 sec, while the LT_{90} values were 212.5 and 88.9 sec, respectively (Table 1). Complete egg mortality of 100% was observed at 440 W after an exposure time of 270 sec (Fig. 1). When considering the reduced emergence of *S. cerealella* adults from treated eggs, the percentage of reduction increased sequentially with lon-

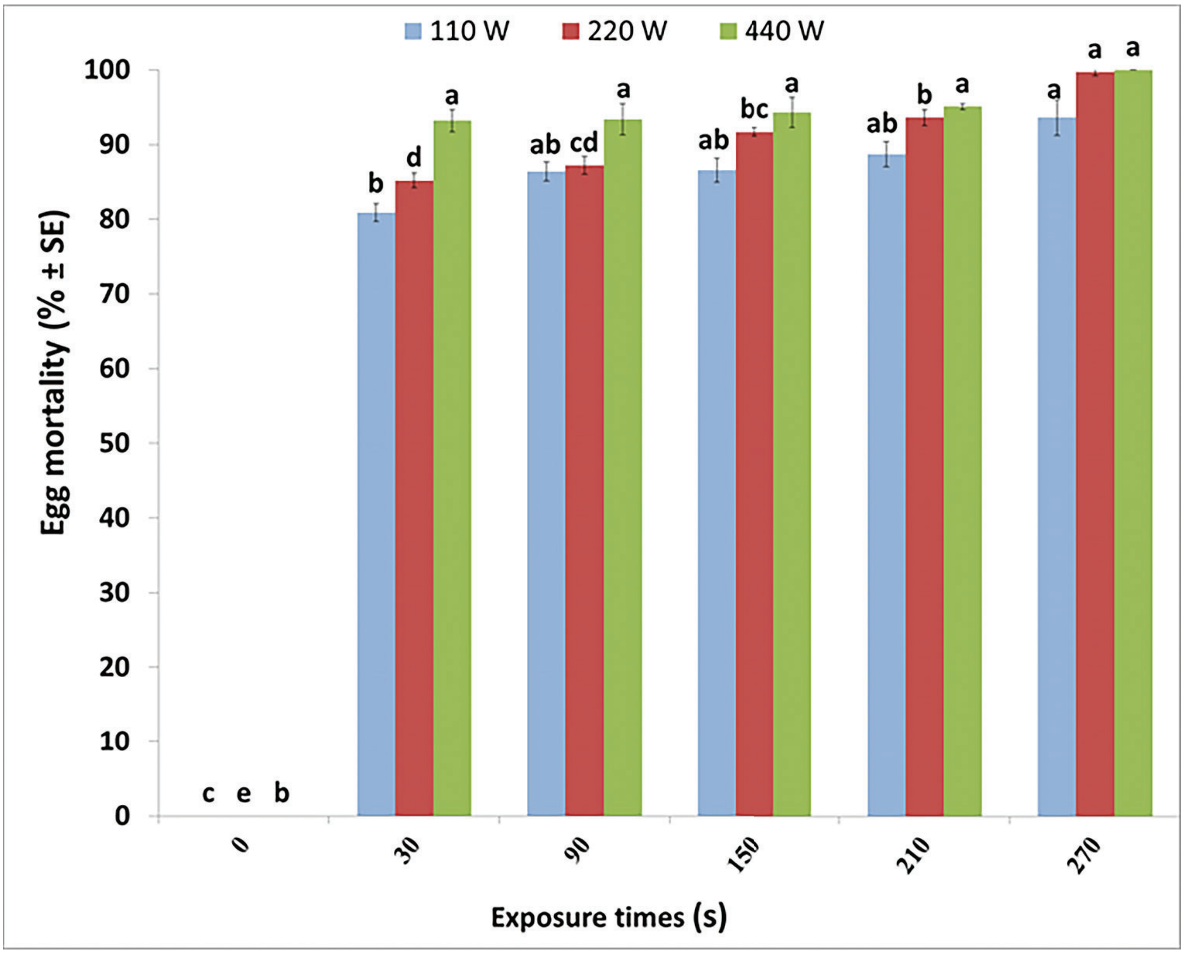

Figure 1. Mean mortality of *Sitotroga cerealella* eggs exposed to different microwave powers (W) for various exposure times (seconds-s). Different letters on top of the bars indicate statistically significant differences in all cases (df =5, 18, $p < 0.05$).

Table 1. LT_{50} and LT_{90} values for eggs of *Sitotroga cerealella* exposed to different microwave powers (W).

Microwave powers (W)	LT_{50} (sec)	LT_{90} (sec)	Confidence limits (sec) of LT_{50}		Confidence limits (sec) of LT_{90}		Slope ± SE	(χ^2)	*P*
			Lower	Upper	Lower	Upper			
110	0.62	212.5	0.16	1.40	114.5	506.4	0.505±0.061	1.48	0.915
220	1.31	88.9	0.002	7.12	42.47	146.01	0.700±0.210	3.05	0.384

ger exposure periods or higher MP levels. With MP levels of 220 and 440 W, the reduction in adult emergence reached 100% after 210 and 270 sec, respectively (Table 2).

Treatment of larvae and pupae by MP and their latent effects

Table 2 indicates the reduction in adult emergence from fourth instar larvae and 5-day-old pupae of *S. cerealella* under different exposure periods. The reduction in adult emergence of *S. cerealella* from treated larvae or pupae increased gradually with an increase in either microwave power (MP) or exposure period. The highest percentage reduction in adult emergence resulted from treated larvae at 99.8% (Table 2) with LT_{50} and LT_{90} values of 0.96 and 123.4 sec, respectively (Table 3), and from pupae at 100% (Table 2) with LT_{50} and LT_{90} values of 110.1 and 517.9 sec, respectively (Table 3) 270 sec after treatment under 220 W of MP. Additionally, complete reduction in adult emergence was observed in larvae and pupae at exposure times of 150, 210, and 270 sec under 440 W of MP.

Treatment of adults by MP

The mortality percentage of *S. cerealella* adults increased with longer exposure periods to MP (Table 4). Full adult mortality reached 100% 3 days after treatment at 110 W of MP with exposure times of 150, 210, and 270 sec. Complete adult mortality was achieved 2 days after treatment at 220 W with exposure times of 210 and 270 sec, and after 1 day at 440 W with exposure times of 150, 210, and 270 sec.

The major chemical components of wheat grains treated with MP

Table 5 displays the main chemical components of untreated and treated wheat grains at two MP (220 W for 270 sec and 440 W for 90 sec). The treated wheat with MP had slightly lower levels of all chemical components except for fibre. The treated wheat grains with two MP, showed a slight reduction in the percentage of relative content of protein (0.05 and 0.47%), fat (1.24 and 1.43%), carbohydrates (1.18 and 2.08%), moisture (4.29 and 3.61%) and ash (0.03 and 0.08%). The highest increases in fibre (0.56 and 0.09%) were noted in the treated wheat compared to the untreated wheat grains, respectively.

Discussion

Numerous safer techniques have been proposed as substitutes for methyl bromide since it was added to the list of substances that deplete the ozone layer (UNEP, 1995). One of these techniques is microwave irradiation which has shown potential in managing postharvest insects (Manickavasagan *et al*., 2013; Sadeghi *et al*., 2018). Our results indicate that as exposure time or microwave power (MP) increased, the percentage of treated *S. cerealella* eggs that were killed also increased, leading to a suppression of adult emergence compared to the control group. These findings are in accordance with Baysal *et al.* (1998) who found that MP of 90 sec was sufficient to control *Ephestia cautella* (Walker) on figs and destroy the insect's eggs. Vadivambal *et al.* (2010a) revealed that samples with *Tribolium castaneum* eggs were most vulnerable when exposed to 200, 300, 400, or 500 W for 28 or 56 sec. Abo-El-Saad *et al.* (2011) demonstrated that complete inhibition of egg

Table 2. Reduction percentages of adult emergence from *S. cerealella* immature stages (eggs, larvae and pupae) exposed to different microwave powers (W) for various exposure times.

Exposure times (sec)	Reduction percentages of adult emergence (% ± SE)								
	110 W			220 W			440 W		
	Eggs	Larvae	Pupae	Eggs	Larvae	Pupae	Eggs	Larvae	Pupae
Control	0.0±0.0c	0.0±0.0e	0.0±0.0e	0.0±0.0c	0.0±0.0d	0.0±0.0e	0.0±0.0c	0.0±0.0d	0.0±0.0d
30	86.2±1.3b	74.8±1.0d	10.5±1.8d	88.1±1.8b	82.7±1.4c	20.9±1.7d	90.3±1.2b	87.5±2.8c	52.2±3.1c
90	87.8±1.3b	79.0±1.6cd	17.7±1.7cd	93.1±1.4b	83.0±1.0c	28.5±2.5d	94.9±2.1b	96.2±1.6b	94.7±1.8b
150	90.3±1.2b	83.3±1.2bc	23.3±1.6bc	94.4±1.7b	86.2±1.8c	52.9±1.6c	97.0±1.9b	100.0±0.0a	100.0±0.0a
210	92.2±1.0ab	86.4±2.5ab	32.2±1.4b	100.0±0.0a	93.9±1.8b	84.4±1.7b	100.0±0.0a	100.0±0.0a	100.0±0.0a
270	96.1±1.1a	92.1±0.8a	50.5±1.0a	100.0±0.0a	99.8±0.2a	100.0±0.0a	100.0±0.0a	100.0±0.0a	100.0±0.0a
F	259.5	619.3	65.2	361.7	575.3	216	354.2	464.2	311.1
P	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Values within a column sharing the same letter are not significantly different (df =5, 18, $p < 0.05$).

Table 3. LT_{50} and LT_{90} values for larvae and pupae of *Sitotroga cerealella* exposed to different microwave powers (W).

Microwave powers (W)	Insect stage	LT_{50} (sec)	LT_{90} (sec)	Confidence limits (sec) of LT_{50}		Confidence limits (sec) of LT_{90}		Slope ± SE	(χ^2)	*P*
				Lower	Upper	Lower	Upper			
110	**Larvae**	3.38	351.8	0.02	12.77	193.4	2313.8	0.635±0.191	2.29	0.514
	Pupae	405.9	4220.9	292.4	731.6	1771.9	23297.8	1.26±0.213	7.52	0.057
220	**Larvae**	0.96	123.4	0.09	1.96	57.14	609.6	0.609±0.065	13.19	0.022
	Pupae	110.1	517.9	73.9	166.6	487.3	1799.4	1.90±0.175	24.50	0.002

Table 4. Mean mortality (% ± SE) of *Sitotroga cerealella* adults exposed to different microwave powers (W) for five exposure times after 1, 2 and 3 days of treatment.

Exposure times (sec)	Adult mortality (% ± SE)								
	110 W			220 W			440 W		
	1 day	2 days	3 days	1 day	2 days	3 days	1 day	2 days	3 days
Control	0.0±0.0d	0.0±0.0c	0.0±0.0d	0.0±0.0d	0.0±0.0d	0.0±0.0c	0.0±0.0d	0.0±0.0c	0.0±0.0
30	9.5±3.4c	27.8±3.9b	61.7±1.2c	41.1±3.4c	50.0±5.8c	66.6±1.7b	80.9±2.1c	88.9±3.9b	100.0±0.0
90	27.8±1.9b	38.9±2.0b	83.3±3.1b	54.7±1.8b	61.1±3.9b	100.0±0.0a	94.4±2.7b	100.0±0.0a	100.0±0.0
150	34.5±2.1b	60.0±1.2a	100.0±0.0a	62.2±1.7b	66.7±1.2bc	100.0±0.0a	100.0±0.0a	100.0±0.0a	100.0±0.0
210	62.5±3.1a	66.6±1.4a	100.0±0.0a	83.3±3.1a	100.0±0.0a	100.0±0.0a	100.0±0.0a	100.0±0.0a	100.0±0.0
270	66.7±3.2a	66.7±4.7a	100.0±0.0a	86.7±2.5a	100.0±0.0a	100.0±0.0a	100.0±0.0a	100.0±0.0a	100.0±0.0
F	70.6	123.4	619.3	224.9	221.0	814.9	357.0	375.2	
P	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	

Values within a column sharing the same letter are not significantly different (df =5, 18, $p < 0.05$).

Table 5. Major chemical components of wheat grains treated with two microwave powers (220 W for 270 sec and 440 W for 90 sec).

Component (%)	Chemical components of wheat grains				
	220 W (270 sec)	440 W (90 sec)	Untreated	F	P
Protein	13.65a (–0.05)*	13.23a (–0.47)	13.7a	0.118	0.891
Fat	1.56a (–1.24)	1.37a (–1.43)	2.80a	2.374	0.174
Carbohydrates	53.92a (–1.18)	53.02a (–2.08)	55.1a	0.237	0.796
Moisture	9.01b (–4.29)	9.69b (–3.61)	13.3a	9.42	0.014
Fibre	3.46a (+0.56)	2.99a (+ 0.09)	2.90a	0.363	0.709
Ash	1.67a (–0.03)	1.62a (–0.08)	1.70a	0.251	0.786

* Percentage of decrease (–) and increase (+)
Values within a raw sharing the same letter are not significantly different (df =2, 6, $p < 0.05$).

hatchability in *E. cautella* was achieved with 100% of 2450 MHz after 10 and 15 sec. Azizoglu *et al.* (2011) showed that full mortality of *Ephestia kuehniella* (Zeller) eggs occurred at 150 and 600 W after 300 and 10 sec, respectively. Darwish *et al.* (2014) observed that egg mortality in *E. kuehniella* reached 100% after 300 and 120 sec of exposure to 330 and 550 W, respectively. Our results indicate that full egg mortality in *S. cerealella* was achieved with the highest MP (440 W) and 270 sec of exposure. This rapid mortality may be attributed to the detrimental effects of microwave radiation on insects, particularly on embryonic cells which divide and expand quickly compared to other cells in immature stages (Zhao *et al.,* 2007).

Additionally, the current investigation demonstrated that *S. cerealella* larvae and pupae were susceptible to MP similar to the egg stage. These two stages were impacted by short exposure times of MP, resulting in a decrease in adult emergence from treated larvae and pupae of *S. cerealella*, and complete suppression of adult emergence at higher MP levels. García-Mosqueda *et al.* (2019) revealed that using microwave powers of 293, 390, and 475 W for exposure times of 56, 40, and 37 sec led to complete larval mortality of *S. cerealella*. The ability of microwaves to penetrate dielectric materials deeply and produce full-volume heating makes them more effective against *S. cerealella* larvae and pupae. These findings could be crucial in eliminating insects hidden within stored grains (Qu *et al.,* 2017; Gillani *et al.,* 2022).

Moreover, our results are in agreement with results on microwave treatments on other insect pests. Vadivambal *et al.* (2006), who stated that 100% mortality was observed at 500 W for pupae of *T. castaneum*. Al-Azab and Abo-El-aad (2007) observed that treating infested dates with MP for 20 sec was highly effective in killing *E. cautella* pupae. Vadivambal *et al.* (2010b) also showed that full mortality of *Sitophilus zeamais* (Motschulsky) and *T. castaneum* larvae was achieved at 600 W for 14 sec and 500 W for 28 sec, while for *Plodia interpunctella* (Hübner) larvae, 100% mortality was attained at 500 W for 14 sec and 400 W for 28 sec. Manickavasagan *et al.* (2013) discovered that using two microwave powers (600 and 800 W) for 40 and 30 sec resulted in complete larval mortality of *T. castaneum*. Darwish *et al.* (2014) also found that larval and pupal mortality of *E. kuehniella* reached 100% after 300 and 120 sec of exposure to 330 and 550 W for larvae, and 240 sec at 550 W for pupae. Pandir and Guven (2014) demonstrated that complete mortality of *E. kuehniella* larvae was achieved with 70 W for 50 sec. Naher *et al.* (2015) observed strong larval mortality of *E. cautella* (90%, 96.7%, and 100%) with microwave powers of 600, 800, and 1000 W at 10 sec of exposure, respectively. Full pupal mortality (100%) was achieved with 800 W and 18 sec of exposure. Tayeb *et al.* (2018) showed that mortality of treated larvae and pupae of *T. castaneum* was 100% with a power of 800 W and exposure time of 20 sec.

The current results demonstrate that the majority of *S. cerealella* moths had higher sensitivity to MP compared to immature stages, reaching almost complete mortality at most tested MP levels with shorter exposure times. Our findings are consistent with El-Disouky (2002) demonstrated that MP treatment of adult *Sitophilus oryzae* (L.) for 25 sec was highly effective, resulting in 100% mortality. Trandeel (2003) found that 19 sec of exposure to MP (2450 MHz) was necessary for *T. castaneum* to achieve 50% mortality. Abo-El-Saad *et al.* (2011) reported that adult mortality of *E. cautella* reached 100% at 60% power of 2450 MHz after 15 sec of exposure. Manickavasagan *et al.* (2013) demonstrated that exposure to 800 W of MP for 30 sec resulted in full mortality of adult *T. castaneum*, while 40 sec of exposure caused full mortality of *Oryzaephilus surinamensis* (L.). Abed *et al.* (2023) showed that 700 W of MP for 30 sec caused complete adult mortality of *S. oryzae*.

Our results indicate that two microwave powers (220 and 440 W) applied for 270 and 90 sec, respectively, cause changes in the chemical components of wheat grains. These changes include a slight reduction in protein, carbohydrates, fat, moisture, and ash contents, as well as a slight increase in fibre content. Our results are in accordance with several studies showing that microwave power induces slight changes in the chemical components of treated stored products (Oomah *et al.,* 2014; Zhong *et al.,* 2019; Peng *et al.,* 2021; Feng *et al.,* 2023).

Conclusion

The tested MP 110, 220, and 440 W had a lethal impact on all life stages of *S. cerealella*. All stages were sensitive to the MP resulting in reduced adult emergence from immature stages and a slight decrease in the chemical components of wheat grains. Our research indicates that MP could be a beneficial alternative for managing *S. cerealella* moderating potential issues associated with the widespread use of chemical insecticides such as environmental pollution and the development of resistance. However, further research is needed to determine the potential long-term effects of MP on the chemical composition of stored grains.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Αποτελεσματικότητα της ακτινοβολίας μικροκυμάτων στα βιολογικά στάδια του *Sitotroga cerealella* και η επίδρασή της στη χημική σύνθεση των σπόρων σιταριού

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Περίληψη Η αποτελεσματικότητα ακτινοβολίας μικροκυμάτων διαφορετικής ισχύος (110, 220 και 440 W) αξιολογήθηκε για πέντε χρόνους έκθεσης εναντίον διαφορετικών βιολογικών σταδίων του εντόμου αποθηκών *Sitotroga cerealella*. Εκτιμήθηκε το ποσοστό θνησιμότητας των βιολογικών σταδίων, η έξο-

δος των ενηλίκων και η επίδραση στη χημική σύσταση των σπόρων σιταριού. Η πλήρης θνησιμότητα των ωών (100%) επιτεύχθηκε στην ισχύ των 440 W και σε χρόνο έκθεσης 270 δευτερολέπτων. Η αύξηση της ισχύος των μικροκυμάτων επηρέασε τη δράση τους στις προνύμφες και νύμφες του εντόμου, με αποτέλεσμα τη μείωση της εμφάνισης ενηλίκων. Επιπλέον, η πλήρης θνησιμότητα των ενηλίκων αυξήθηκε με μεγαλύτερες περιόδους έκθεσης στην ακτινοβολία μικροκυμάτων, φτάνοντας το 100%, τρεις ημέρες μετά την έκθεση στην ισχύ των 110 W για 150, 210 και 270 δευτερόλεπτα. Πλήρης θνησιμότητα των ενηλίκων επιτεύχθηκε δύο ημέρες μετά την έκθεση σε ακτινοβολία μικροκυμάτων ισχύος 220 W για 210 και 270 δευτερόλεπτα, και μία ημέρα μετά την έκθεση στην ισχύ των 440 W για 150, 210 και 270 δευτερόλεπτα. Επιπλέον, η ακτινοβολία μικροκυμάτων προκάλεσε μικρή μείωση στα χημικά συστατικά των σπόρων σιταριού, εκτός από την περιεκτικότητα σε φυτικές ίνες. Από τα αποτελέσματα φαίνεται ότι η ακτινοβολία μικροκυμάτων μπορεί να αποτελέσει μια χρήσιμη μέθοδο για την αντιμετώπιση του *S. cerealella*.

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