

# Susceptibility of *Tribolium castaneum* (Coleoptera: Tenebrionidae) Life Stages to Flameless Catalytic Infrared Radiation

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**ABSTRACT** The susceptibility of various life stages of the red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), a pest of stored wheat, *Triticum aestivum* L., to flameless catalytic infrared radiation in the 3–7- $\mu$ m range was evaluated in the laboratory. Immature stages were collected from flour infested with *T. castaneum* adults only for 1 d. Stages collected after 1 d represented eggs (collected on day 0); those collected after 7, 14, and 21 d from day 0 represented larvae in different developmental stages, whereas those collected after 24 d represented pupae. Adults (2 wk old) were collected after 42 d. Each of these stages was exposed for 45 or 60 s in 113.5 or 227.0 g of wheat at a distance of 8.0 or 12.7 cm from a bench top infrared emitter. The mean temperatures attained during exposures were measured continuously using a noncontact infrared thermometer connected to a computer. The mean grain temperatures attained increased with an increase in exposure time and were inversely related to distance from the emitter. Grain quantity least influenced mean temperatures attained. Pupae were the least susceptible stage and larvae collected after 7 d were the most susceptible stage. Variation in probability of death of various life stages decreased with an increase in mean grain temperatures attained. All life stages were killed after a 60-s exposure at a distance of 8.0 cm from the emitter in 113.5 g of wheat, where the mean  $\pm$  SE temperatures attained ranged from 107.6  $\pm$  1.2 to 111.4  $\pm$  0.5°C. Our laboratory results using small grain quantities and short exposure times showed that flameless catalytic infrared radiation can be a valuable tool for managing insects in stored organic and nonorganic wheat.

**KEY WORDS** stored grain, nonchemical control, integrated pest management

The damage contributed by insects to stored wheat, *Triticum aestivum* L., depends on the length of storage, grain moisture, and the effectiveness of pest management tactics (Storey et al. 1984, Reed and Pedersen 1987, Kenkel et al. 1993, Martin et al. 1997). The most common and damaging insect species associated with wheat stored on farms and at elevators in Kansas and neighboring states is the lesser grain borer, *Rhizopertha dominica* (F.) (Coleoptera: Bostrichidae) (Reed et al. 1991, Dowdy and McGaughy 1994, Vela-Coiffier et al. 1997, Reed et al. 2003). The rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), and red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), are found to a lesser extent in wheat stored on farms and at elevators in Kansas (Reed et al. 1991, 2003); however, the latter species is more common than the former. Activity of all three

species of insects was observed outside of farm bins (Dowdy and McGaughy 1994).

There has been documented resistance to traditionally used organophosphate grain protectants and the fumigant phosphine in *R. dominica*, *S. oryzae*, and *T. castaneum* (Subramanyam and Hagstrum 1996). In addition, trace amounts of chemical residues, which result from use of grain protectants, may be unacceptable to foreign and domestic buyers. Therefore, there is a need to explore nonchemical stored product insect management methods, especially environmentally benign technologies, to replace or complement currently used insecticides for protecting stored grains.

Infrared radiation in the 3–7- $\mu$ m range is one such technology that has shown promise against insects associated with stored grains in laboratory tests (Schroeder 1960, Schroeder and Rosberg 1960, Tilton and Schroeder 1963, Cogburn 1967, Cogburn et al. 1971, Kirkpatrick and Tilton 1972, Kirkpatrick et al. 1972, Kirkpatrick 1973, Kirkpatrick and Cagle 1978, Tilton et al. 1983). The infrared radiation in those previous evaluations was generated when natural gas or propane was combusted over ceramic panels in the presence of oxygen. These gas-fired radiation sources were of high intensity, producing 14.07 kW/h (48,000 BTU/h) of heat energy and temperatures that were

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close to 930°C. Such open flames and high temperatures are undesirable for use in grain-handling establishments or mills for continuous online disinfection of grain because of explosion hazards. In all of the previous studies reported above, the grain temperatures were measured with a thermocouple after infrared exposure, resulting in underestimating the temperatures actually attained by grains. In addition, the exact life stages of insects exposed were not confirmed.

Flameless catalytic infrared radiation is a new technology developed by Catalytic Drying Technologies, LLC (Independence, KS) (<http://www.catalyticdrying.com>). In flameless infrared emitters, propane or natural gas chemically reacts with oxygen in the presence of a platinum catalyst below flame temperatures (500°C), delivering peak infrared radiant energy in the 3–7- $\mu\text{m}$  range. The only co-products of this reaction are traces of carbon dioxide and water. Catalytic Drying Technologies, LLC, received an award from the U.S. Environmental Protection Agency's Pollution Prevention Program for developing flameless infrared radiation sources, under the "Environmentally Preferable Products" category. The objective of this research was to evaluate the susceptibility of different life stages of *T. castaneum* exposed to flameless catalytic infrared radiation energy.

### Materials and Methods

**Insects Rearing.** Laboratory cultures of *T. castaneum* were reared under controlled conditions in the Department of Grain Science and Industry, Kansas State University, Manhattan, KS, on 95% bleached wheat flour and 5% (by weight) of brewer's yeast (Lesaffre Yeast Corporation, Milwaukee, WI) in growth chambers (model I-36 VL; Percival Scientific, Perry, IA) at 28°C, 65% RH, and a photoperiod of 14:10 (L:D) h. This species has been in culture in the Department of Grain Science and Industry (Manhattan, KS) for 11 yr.

**Obtaining Different Life Stages (Ages) of *T. castaneum*.** To obtain various life stages or ages of *T. castaneum*, 100 unsexed 2-wk-old adults from cultures were used to infest several jars containing 100-g of flour plus 5% (by weight) yeast diet for 1 d after which the adults were removed and the flour was incubated at 28°C, 65% RH, and a photoperiod of 14:10 (L:D) h. Before use in tests, the diet was sifted through a 250- $\mu\text{m}$  sieve (Seedbuero Equipment Company, Chicago, IL). The procedures for extracting eggs, young larvae, old larvae, pupae, and adults of *T. castaneum* for use in tests were similar to those described by Mahroof et al. (2003). To collect eggs, contents in jars with adults were sifted after one day using 840- and 250- $\mu\text{m}$  sieves. Adults were retained on the 840- $\mu\text{m}$  sieve and eggs on the 250- $\mu\text{m}$  sieve. Eggs were counted and gently removed with a hairbrush on to 9-cm glass petri dishes. The eggs represented age 0 (day 0) for *T. castaneum*. To extract other life stages, infested jars infested with adults removed were held at 28°C and 65% RH for 7, 14, and 21 d after day 1 to obtain larvae in different developmental stages. Jars held for 24 d

represented the pupal stage. Adults were evident on day 28. Adults from these jars were held for another 2 wk to obtain 2-wk-old adults or 42-d-old insects. Adults were obtained by sifting the infested jar contents over an 840- $\mu\text{m}$  sieve.

**Grain Infestation and Infrared Treatments.** Three factors that influence grain temperatures attained and consequently insect responses were evaluated. The factors explored included insect age, grain quantity (113.5 and 227.0 g), distance from the emitter (8.0 and 12.7 cm), and exposure time (45 and 60 s). Organic wheat (Heartland Mills, Marienthal, KS) was weighed (113.5 or 227.0 g), placed in individual 0.45-liter glass jars, and covered with wire mesh screens and filter paper lids. These jars were placed in a growth chamber at 28°C and 65% RH for 1 wk to equilibrate the moisture content to 12%. Equilibrated wheat for the various treatments received 100 *T. castaneum* individuals of a specific age, except in the case of eggs where 50 eggs collected 1 d were added to the wheat. Infested wheat was exposed to the benchtop infrared emitter for 45 or 60 s at a distance of 8.0 or 12.0 cm (see below). Each of the infrared treatment combinations was replicated three times. Control wheat included wheat infested similarly but unexposed to infrared treatment. The control treatments were replicated four times.

**Benchtop Infrared Emitter.** The benchtop infrared emitter used in this study was donated by Catalytic Drying Technologies, LLC. The infrared emitter elements are housed in a circular stainless steel casing with a surface area of 613.4 cm<sup>2</sup>. Propane (473-ml cylinder, Ozark Trail Propane Fuel, Bentonville, AR) was supplied to the heating element via a hose at a pressure of 28.0 cm of water column. Grain samples for infrared exposure were placed in a 3.8-cm-deep steel pan of 27.9 cm in diameter, with a 43-cm-long steel handle. The 113.5 or 227.0 g of wheat placed in the steel pan were exposed to infrared radiation in a monolayer. Thirteen measurements, taken with an infrared thermometer (Khamis et al. 2010), showed the temperature at emitter surface ranged from 335 to 474°C, with higher temperatures recorded near the center of the emitter. Therefore, temperature attained by wheat was measured at the center of the pan. This method is superior to the method used previously in which the grain after infrared exposure was placed in a container and the temperature measured with a thermocouple.

**Continuous Temperature Measurements During Infrared Exposure.** The surface temperature of infested grain during infrared exposures was continuously recorded using a noncontact infrared thermometer (Raytek Ranger MX4TM, model 4TP78, Santa Cruz, CA). This thermometer works in the 8–14- $\mu\text{m}$  range, and the emissivity was set at 0.95. The infrared thermometer was previously calibrated with a mercury thermometer and was found to record temperatures as accurately as a mercury thermometer (Khamis 2009, Khamis et al. 2010). The infrared thermometer was connected to a laptop via a standard RS-232 cable to acquire "real-time" temperature data

every second. The temperature data acquisition program was written by the Electronic Design Laboratory, Kansas State University, in LABView (National Instruments Corporation, Austin, TX).

**Assessment of Insect Mortality.** After infrared exposure, the grain and any grain debris were returned to the original glass jar, and incubated at 28°C and 65% RH. Adult mortality was assessed 24 h after infrared exposure based on number of dead adults of the total exposed. Immature stages were reared to the adult stage on the same grain, and their mortality was based on number of adults that failed to emerge out of the total exposed. Similar assessments were made on infested grain that was not exposed to infrared radiation.

**Experimental Design and Data Analysis.** The experiment was run as a completely randomized design. The time-dependent temperature profile for each replicate was averaged over time to obtain a mean temperature attained by wheat during the exposure period. The mean wheat temperature attained for any given insect age, wheat quantity, and exposure time combination between 8.0- and 12.7-cm distance from the emitter surface was compared ( $\alpha = 0.05$ ) by using two sample *t*-tests for equal variances (SAS Institute 2002). Two sample *t*-tests were used to compare differences in mean temperatures attained between a 45- and 60-s exposure at any given insect age, grain quantity, and distance from heater. In addition, comparisons were also made of mean temperatures attained between 113.5 and 227.0 g of grain at any given insect age, distance from heater, and exposure time.

Linear regression analysis was done on the same treatment combinations (specific grain quantity, distance from emitter, and exposure time) across all life stages to examine whether various life stages received same heat energy (measured as temperature) at  $\alpha = 0.05$  (SAS Institute 2002). The slopes of the linear regressions were tested for deviation from zero.

The main effect of insect age, wheat quantity, distance from emitter, and exposure time and their two-way interactions on the probability of death were determined using logistic regression at  $\alpha = 0.05$  (SAS Institute 2002). Odds ratios from logistic regression were used to show differences in susceptibility (odds of dying) of various life stages exposed to infrared radiation. The odds ratio for adults (1) was used as a

**Table 1.** Emergence of *T. castaneum* adults from immatures on untreated wheat

Insect age (d) <sup>a</sup>	Mean $\pm$ SE no. adults in	
	113.5 g	227.0 g
0 <sup>b</sup>	35.3 $\pm$ 4.9	36.0 $\pm$ 5.4
7	100.0	99.5 $\pm$ 0.5
14	100.0	100.0
21	100.0	99.5 $\pm$ 0.5
24	99.3 $\pm$ 0.5	100.0

Each mean is based on  $n = 4$  replications.

<sup>a</sup> To collect various ages of immature stages, *T. castaneum* adults were placed on flour for 1 d, after which the adults were removed at 28°C and 65% RH. Insects collected on after 1 d represented eggs (day 0), and those collected after 7, 14, and 21 d represented larvae in various developmental stages. Insects collected after 24 d were pupae.

<sup>b</sup> For eggs, 50 individuals were used; for the other immature stages, 100 individuals were used.

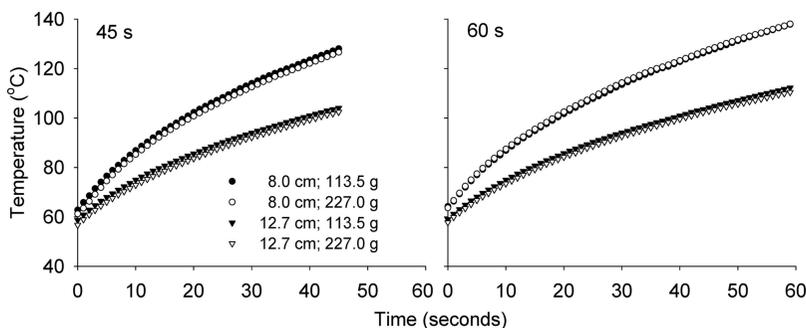
reference. A ratio  $>1$  showed that a life stage was more susceptible than adults to infrared, whereas a ratio  $<1$  showed that a stage was less susceptible than adults.

## Results

**Emergence of *T. castaneum* Adults From Immatures on Untreated (Control) Wheat.** On untreated 113.5 and 227.0 g of wheat, 71–72% of the introduced eggs became adults (Table 1). Nearly all of the individual larvae and pupae added to untreated wheat emerged as adults and the survival of these stages was  $\geq 99\%$ .

**Temperature Profiles During Infrared Exposure.** The time-dependent temperature profile, averaged every second from replicated data, was plotted as a function of time for 113.5 and 227.0 g of grain exposed for 45 and 60 s at 8.0 and 12.7 cm from the infrared emitter. There were eight temperature profiles for each insect age. A comparison of temperature profiles across various ages showed that for any given quantity of grain, distance from emitter, and exposure time, the profiles were essentially similar. Therefore, two of the 48 graphs were selected to show a typical time-dependent temperature profile (Fig. 1).

In general, mean grain temperatures were higher in 113.5 g of wheat at a given distance from emitter and exposure time. Similarly, mean grain temperatures



**Fig. 1.** Generalized time-dependent temperature profile attained with different quantities of wheat exposed at 8.0 and 12.7 cm from the emitter for 45 and 60 s.

**Table 2.** Emergence of *T. castaneum* adults from infested wheat in various infrared-exposed treatments, mean temperature attained by wheat, and probability of insect death

Insect age (d) <sup>a</sup>	Grain quantity (g)	Distance from emitter (cm)	Exposure time (s)	Mean temp (°C)	Mean no. adults	Probability of death	
0	113.5	8.0	45	101.3 ± 1.1	0	0.98	
			60	107.6 ± 1.2	0	1.00	
		12.7	45	83.1 ± 2.0	4.0 ± 1.7	0.89	
	7	227.0	8.0	60	89.2 ± 0.3	14.7 ± 2.0	0.98
				45	97.3 ± 0.9	119.3 ± 8.7	0.87
			12.7	60	108.1 ± 0.6	0.3 ± 0.3	0.98
14		113.5	8.0	45	81.9 ± 1.0	12.7 ± 3.2	0.47
				60	85.9 ± 1.6	3.3 ± 1.3	0.87
			12.7	45	103.5 ± 0.2	0	1.00
	21	227.0	8.0	60	111.4 ± 0.5	0	1.00
				45	83.7 ± 0.1	0.3 ± 0.3	0.78
			12.7	60	87.3 ± 0.6	0	1.00
24		113.5	8.0	45	100.1 ± 0.1	0	0.96
				60	108.5 ± 0.8	0	1.00
			12.7	45	83.7 ± 0.6	0.3 ± 0.3	0.78
	42 (adults) <sup>b</sup>	227.0	8.0	60	87.3 ± 0.6	0	0.96
				45	100.1 ± 0.1	0	0.96
			12.7	45	108.5 ± 0.8	0	1.00
42 (adults) <sup>b</sup>		113.5	8.0	60	83.7 ± 0.6	0.3 ± 0.3	0.78
				45	87.3 ± 0.6	0	0.96
			12.7	45	103.2 ± 1.3	0.3 ± 0.3	0.99
	42 (adults) <sup>b</sup>	227.0	8.0	60	110.6 ± 0.6	0	1.00
				45	85.0 ± 0.5	0.3 ± 0.3	0.95
			12.7	60	91.3 ± 0.4	0	0.99
42 (adults) <sup>b</sup>		113.5	8.0	45	101.8 ± 0.6	4.3 ± 1.9	0.95
				60	109.3 ± 0.7	0	0.99
			12.7	45	83.7 ± 1.0	31.7 ± 8.4	0.69
	42 (adults) <sup>b</sup>	227.0	8.0	60	87.8 ± 0.3	65.7 ± 8.1	0.88
				45	103.5 ± 0.3	0	0.99
			12.7	60	111.4 ± 0.5	0	1.00
42 (adults) <sup>b</sup>		113.5	8.0	45	84.4 ± 0.9	2.3 ± 0.9	0.95
				60	92.0 ± 1.6	1.0 ± 0.6	0.99
			12.7	45	100.6 ± 0.9	8.7 ± 4.1	0.94
	42 (adults) <sup>b</sup>	227.0	8.0	60	109.8 ± 0.7	0.7 ± 0.3	0.99
				45	82.7 ± 0.6	66.3 ± 2.3	0.67
			12.7	60	87.4 ± 0.3	12.7 ± 1.8	0.94
42 (adults) <sup>b</sup>		113.5	8.0	45	103.3 ± 1.3	0	0.99
				60	108.5 ± 2.7	0	1.00
			12.7	45	80.9 ± 1.7	16.0 ± 6.7	0.90
	42 (adults) <sup>b</sup>	227.0	8.0	60	86.4 ± 1.4	0	0.99
				45	103.1 ± 1.4	21.7 ± 11.2	0.89
			12.7	60	113.1 ± 0.1	0	0.99
42 (adults) <sup>b</sup>		113.5	8.0	45	82.9 ± 0.7	59.3 ± 9.8	0.50
				60	84.8 ± 0.8	13.7 ± 0.8	0.88
			12.7	45	102.3 ± 0.3	0	0.99
	42 (adults) <sup>b</sup>	227.0	8.0	60	108.0 ± 0.3	0	1.00
				45	82.6 ± 1.6	14.3 ± 6.4	0.92
			12.7	60	87.3 ± 0.9	2.0 ± 1.2	0.99
42 (adults) <sup>b</sup>		113.5	8.0	45	100.0 ± 0.5	6.3 ± 0.9	0.91
				60	106.6 ± 0.9	0	0.99
			12.7	45	82.2 ± 0.3	42.3 ± 2.8	0.56
	42 (adults) <sup>b</sup>	227.0	8.0	60	86.9 ± 0.7	9.0 ± 3.5	0.91

<sup>a</sup> See footnote to Table 1 regarding how various ages of insects were collected.

<sup>b</sup> Adults started to emerge from flour infested with *T. castaneum* adults after 28 d. These adults were held at 28°C and 65% RH for 2 wk before use in tests.

were higher when wheat was exposed at a distance of 8.0 cm than at 12.7 cm from the emitter and after a 60-s exposure than after a 45-s exposure (Table 2).

Two sample *t*-tests for each life stage of *T. castaneum* age (0, 7, 14, 21, 24, and 42 d) have shown that the mean temperature attained by 113.5 or 227.0 g of wheat during a 45- or 60-s exposure was significantly greater at 8.0 cm from the emitter when compared with mean temperature attained by wheat at 12.7 cm from the emitter (*t*, range among ages, grain quantities, and exposure times = 7.27–33.46; *df* = 4; *P* < 0.0001). Although the highest mean ± SE grain temperature attained (113.1 ± 0.1°C) was in 227.0 g of wheat exposed for 60 s and at a distance of 8.0 cm from the emitter, higher grain temperatures were generally attained in 113.5 g of wheat exposed for 60 s, at 8.0 cm distance from the emitter surface. The lowest mean ± SE temperature attained (80.9 ± 1.7°C) was in 113.5 g

of grain exposed for 45 s at a distance of 12.7 cm from the emitter surface (Table 2). The mean temperature attained by wheat after a 60-s exposure was significantly and consistently higher than those attained after a 45-s exposure for a given insect age, grain quantity, and distance from the emitter (*t*: range, -3.94 to 15.63; *df* = 4; *P* ≤ 0.017) for 20 of the 24 comparisons. In four comparisons, the mean grain temperatures attained between 45- and 60-s exposures were similar (*t*: range, -1.73 to 2.63; *df* = 4; *P* ≥ 0.058).

In general, of the three factors examined, grain quantity had the least influence on mean grain temperatures attained for any given insect age, distance from heater, and exposure time. In 17 of the 24 comparisons, the difference in mean temperature attained by 113.5 and 227.0 g of wheat was not significant (*t*: range, -1.73 to 2.70; *df* = 4; *P* > 0.052). In seven other cases, mean temperatures attained by 113.5 g of grain

was significantly different than that attained by 227.0 g of grain ( $t$ : range, 3.11–16.33;  $df = 4$ ;  $P \leq 0.036$ ).

Different life stages tested were exposed to same amount of heat energy, based on grain surface temperature measurement in the center of the pan, although as stated by Khamis et al. (2010) the grain near edges will be at a lower temperature than grain at the center of the pan. The slope of the linear regressions between mean temperature attained by 113.5 or 227.0 g of grain at 8.0 or 12.7 cm from the emitter after a 45- or 60-s exposure and the insect age was not significantly different from zero ( $t$ : range among grain quantities, distance from emitter, and exposure times, -1.09 to 1.70;  $n = 6$ ;  $P \geq 0.164$ ).

**Responses of *T. castaneum* Life Stages to Infrared Radiation.** The mortality of *T. castaneum* life stages increased with an increase in the mean grain temperature attained (Table 2). One hundred percent mortality was achieved for all stages in 113.5 g of grain, exposed for 60 s at a distance of 8.0 cm from the emitter, where the mean  $\pm$  SE temperatures attained ranged from  $108.0 \pm 0.3$  to  $111.4 \pm 0.5^\circ\text{C}$ . At the same distance and exposure time, mortality of *T. castaneum* life stages in 227.0 g of grain was 98–100%. Exposure of 227.0 g of grain for 45 s at a distance of 12.7 cm from the emitter resulted in 78–95% mortality. Lower mortalities occurred across life stages in 227.0 g of grain, despite observed high grain temperatures. Although the grain was exposed to infrared radiation in a monolayer, different grain quantities resulted in different insect mortalities, despite reaching the same temperature, indicating that temperature alone was not a factor determining insect lethality.

Logistic regression analysis showed that the probability of death of *T. castaneum* was influenced significantly by insect age ( $\chi^2 = 26.7$ ,  $df = 5$ ,  $P < 0.0001$ ), grain quantity ( $\chi^2 = 67.9$ ,  $df = 1$ ,  $P < 0.0001$ ), distance from emitter ( $\chi^2 = 51.3$ ,  $df = 1$ ,  $P < 0.0001$ ), and exposure time ( $\chi^2 = 97.7$ ,  $df = 1$ ,  $P < 0.0001$ ). All two-way interactions (insect age  $\times$  wheat quantity, insect age  $\times$  distance from heater, insect age  $\times$  exposure time [ $df = 5$ ]; wheat quantity  $\times$  distance from heater, wheat quantity  $\times$  exposure time, and distance from heater  $\times$  exposure time [ $df = 1$ ]) were also highly significant ( $\chi^2$  range, 8.3–44.3;  $P < 0.0001$ ).

Both the insect mortality (probability of death data) and odds ratios showed that pupae of *T. castaneum* were the least susceptible stage (odds ratio, 0.52), followed by eggs (0.66), adults (1), larvae collected after 21 d (1.46), larvae collected after 14 d (1.78), and larvae collected after 7 d (2.86).

The variation in probability of death of various life stages of *T. castaneum* was evident at mean grain temperatures below  $105^\circ\text{C}$  (Fig. 2). Generally, across grain quantities, exposure times, and distance from emitter, all life stages were killed when the mean grain temperatures attained were between 108 and  $111^\circ\text{C}$ .

### Discussion

Nearly 71–99% of the adults emerged from untreated grain. This high adult emergence on untreated

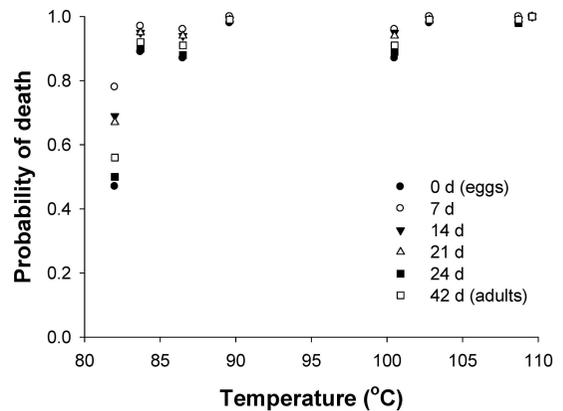


Fig. 2. Probability of death of different life stages of *T. castaneum* as a function of mean wheat temperature.

wheat suggested that the methods used for infesting grain with immatures to gauge effectiveness of infrared radiation was valid and robust.

All life stages or ages of *T. castaneum* received the same amount of infrared energy, because the slopes from linear regression analysis of mean grain temperature attained as a function of insect age for treatment combinations did not significantly deviate from zero. Two sample  $t$ -tests showed that the distance from emitter and exposure time had a greater influence on mean temperatures attained than grain quantity. The mean temperatures attained were inversely related to distance from the emitter but positively related to exposure time.

In general, in infested wheat that attained mean temperature  $\geq 90^\circ\text{C}$ , fewer *T. castaneum* immatures survived and completed development as evidenced by lower number of adults that emerged. Although temperatures attained by the two quantities of grain exposed for a specific time were similar, the mortality of *T. castaneum* was different by 10% among life stages. For example, the mortality of the egg stage in 113.5 g of wheat exposed for 45 s at a distance of 12.7 cm from the emitter was 89% and the mean temperature attained by the grain was  $\approx 83^\circ\text{C}$ . The mean grain temperature was also  $83^\circ\text{C}$  when larvae collected after 7 d were exposed to infrared radiation under similar conditions but the mortality was 78%. This suggested that temperature attained by grain was not the only factor that contributed to insect mortality. In the 3–7- $\mu\text{m}$  range water molecules have the maximum infrared absorption (Sandu 1986, Pan et al. 2008), and differences in water content among life stages may explain differences in the mortality observed. In addition, we did not measure the amount of infrared energy that was absorbed by grain or that reflected by the grain and steel pan could have influenced insect mortality, with some dampening effects at the larger grain quantity used. These aspects warrant further study.

Among the life stages, pupae were less susceptible to infrared, whereas young larvae were highly susceptible, and the variation in susceptibility among stages decreased at temperatures above  $105^\circ\text{C}$ . All life stages

were killed when mean grain temperatures attained were above  $\geq 108^{\circ}\text{C}$ , irrespective of the grain quantity, distance from emitter, and exposure time. However, exposure of 113.5 g of grain to infrared at a distance of 8.0 cm from the emitter for a duration of 60 s consistently produced 100% mortality, irrespective of insect age.

To our knowledge, this is the first report that systematically shows the effects of infrared radiation on various life stages of *T. castaneum* in stored wheat. In summary, our tests show the bench top flameless infrared emitter to be a viable tool for disinfesting stored wheat containing various life stages of *T. castaneum*. At the treatment combinations reported here, wheat subjected to infrared radiation did not show any adverse loss of physical, chemical, rheological, or end-use qualities (Khamis 2009). Large-scale tests need to be conducted to verify our laboratory findings to make this technology commercially viable to grain industry stakeholders.

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