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Management of the red flour beetle, *Tribolium castaneum* (Herbst) using microwave irradiation

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ABSTRACT

The red flour beetle, *Tribolium castaneum* (Herbst), is one of the most destructive secondary pests of stored grains, causing significant quantitative and qualitative losses during storage. The present study evaluated the efficacy of microwave irradiation against *T. castaneum* under laboratory conditions. A domestic microwave oven operating at 2450 MHz was used to expose pre-infested rice grains and different developmental stages (egg, larva, pupa and adult) of *T. castaneum* to five power levels (180, 360, 540, 720 and 900 W) for exposure durations of 30, 60 and 90 s. Microwave irradiation significantly increased insect mortality and reduced adult emergence with increasing power and exposure duration. Adult mortality increased from 13.33% at 180 W for 30 s to 100% at 900 W for 30 s, while complete mortality was achieved at 540 W for 60 s and under all treatments exposed for 90 s. Adult emergence declined from 96.69% to 0% under higher microwave treatments. Stage-specific evaluation revealed that eggs were the most susceptible stage, followed by larvae, adults and pupae. Complete inhibition of adult emergence from eggs was achieved at 720 W for 30 s, whereas complete larval and pupal mortality required 540 W for 30 s and 540 W for 60 s, respectively. The results demonstrate that microwave irradiation is an effective, residue-free and environmentally safe technique for managing *T. castaneum* in stored rice. The study highlights the potential of microwave technology as a sustainable alternative to conventional chemical methods for protecting stored grains.

Keywords: *Adult emergence, Tribolium castaneum, Microwave irradiation, Residue-free grain protection, Stored rice, Stored-product insects and Sustainable pest management*

The red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), is one of the most destructive secondary pests of stored grains and processed food products worldwide. It infests cereals, flour, pulses and other stored commodities, causing significant quantitative and qualitative losses through feeding damage and contamination, thereby reducing grain quality and market value (Hertlein *et al*., 2011).

Management of *T. castaneum* relies primarily on synthetic insecticides and fumigants. However, continuous use of these chemicals has led to insecticide resistance, pesticide residues in food commodities, environmental contamination and adverse effects on non-target organisms. These limitations have created a need for environmentally safe and residue-free alternatives for stored-grain protection (Phillips and Throne, 2010; Hertlein *et al*., 2011).

Microwave irradiation has emerged as a promising non-chemical technology for the management of stored-product insects. Microwave energy produces rapid dielectric heating, causing thermal disruption of insect tissues. Since insects possess higher moisture content than grains, they absorb microwave energy more efficiently, resulting in selective heating and effective insect control with minimal impact on grain quality. The efficacy of microwave treatment depends on microwave power, exposure duration and the developmental stage of the insect.

Therefore, the present study was undertaken to evaluate the efficacy of microwave irradiation at different power levels and exposure durations against pre-infested rice grains and different developmental stages of *T. castaneum* to identify effective treatment

combinations for sustainable management of this important stored-product pest.

MATERIAL AND METHODS

Insect culture

The study was conducted in the Department of Entomology, Agricultural College, Bapatla, India. The Machilipatnam population of *Tribolium castaneum*, which exhibited the highest tolerance to spinosad, was used for the experiment. The culture was maintained under laboratory conditions without insecticide exposure, and healthy insects were used for all bioassays.

Microwave treatments

Microwave treatments were carried out using a domestic microwave oven operating at 2450 MHz with adjustable power levels ranging from 180 to 900 W. Sixteen treatments comprising five power levels (180, 360, 540, 720 and 900 W) at three exposure durations (30, 60 and 90 s) along with an untreated control were evaluated in a completely randomized design with three replications.

Evaluation on pre-infested rice grains

One hundred grams of disinfested rice grains were infested with five pairs of one-day-old adults of *T. castaneum* and allowed to oviposit for seven days. The pre-infested grain samples were exposed to the respective microwave treatments. Adult mortality was recorded one week after treatment, and adult emergence was assessed to determine the effectiveness of microwave irradiation.

Evaluation on developmental stages

The efficacy of microwave irradiation was evaluated separately against eggs, fourth-instar larvae, pupae and freshly emerged adults. Twenty individuals of each immature stage and ten adults were exposed to the respective microwave treatments in 100 g of rice grains. After treatment, samples were maintained under laboratory conditions until completion of development. Observations on egg viability, larval and pupal mortality, adult mortality and adult emergence were recorded according to the developmental stage evaluated.

Statistical analysis

The experiment was conducted in a completely randomized design with three replications. Percentage data were subjected to angular transformation before analysis. The data were analyzed using analysis of variance (ANOVA), and treatment means were separated using the critical difference (CD) test at the 5% level of significance.

RESULTS AND DISCUSSION

Effect of microwave irradiation on *T. castaneum* in pre-infested rice grains

Microwave irradiation significantly reduced the survival and population development of *T. castaneum* in pre-infested rice grains. Adult mortality increased from 13.33% at 180 W for 30 s to 73.33% at 720 W for 30 s, reaching 100% at 900 W for 30 s (Table 1). Likewise, complete mortality was achieved at 540 W and above for 60 s, while all treatments exposed for 90 s resulted in 100% mortality. A corresponding decline in adult emergence from 96.69% at 180 W for 30 s to 25.73% at 720 W for 30 s, followed by complete suppression at higher microwave treatments, clearly demonstrates that microwave irradiation not only killed existing adults but also prevented the successful development of immature stages present in the grain.

The observed increase in mortality with increasing microwave power and exposure duration is attributed to rapid dielectric heating, which elevates the internal body temperature of insects above their physiological tolerance limits. Insects possess considerably higher moisture content than grains and therefore absorb microwave energy more efficiently, resulting in protein denaturation, membrane disruption, enzyme inactivation and ultimately death. The complete inhibition of adult emergence at 900 W for 30 s and e”540 W for 60 s further indicates that microwave treatment effectively destroyed eggs and larvae concealed within the grain mass, preventing subsequent population establishment. Similar observations were reported by Vadivambal *et al*. (2010), who achieved complete mortality of *T. castaneum* adults at 500 W for 28 s, while Miao *et al*. (2026) also reported 100% mortality of *T. castaneum* at 700 W for 60 s, confirming that increasing microwave intensity substantially improves insect control.

Effect of microwave irradiation on different developmental stages.

A significant variation in susceptibility was observed among the developmental stages of *T. castaneum*. Adult emergence from treated eggs

Table 1. Effect of microwave heat treatments at different power levels and exposure durations on per cent adult mortality and adult emergence of *T. castaneum*

Tr. No.	Power level (Watts), Time (Seconds)	Adult mortality (%)**	Adult emergence (%)**
T_1	180 W, 30 s	13.33 (0.37)^{f}	96.69 (1.39)^{b}
T_2	360 W, 30 s	26.67 (0.54)^{e}	69.49 (0.99)^{c}
T_3	540 W, 30 s	46.67 (0.75)^{d}	49.99 (0.78)^{d}
T_4	720 W, 30 s	73.33 (1.03)^{b}	25.73 (0.53)^{e}
T_5	900 W, 30 s	100.00 (1.57)^{a}	0.00 (0.11)^{g}
T_6	180 W, 60 s	23.33 (0.50)^{e}	69.48 (0.99)^{c}
T_7	360 W, 60 s	66.67 (0.96)^{c}	21.32 (0.48)^{f}
T_8	540 W, 60 s	100.00 (1.57)^{a}	0.00 (0.11)^{g}
T_9	720 W, 60 s	100.00 (1.57)^{a}	0.00 (0.11)^{g}
T_{10}	900 W, 60 s	100.00 (1.57)^{a}	0.00 (0.11)^{g}
T_{11}	180 W, 90 s	100.00 (1.57)^{a}	0.00 (0.11)^{g}
T_{12}	360 W, 90 s	100.00 (1.57)^{a}	0.00 (0.11)^{g}
T_{13}	540 W, 90 s	100.00 (1.57)^{a}	0.00 (0.11)^{g}
T_{14}	720 W, 90 s	100.00 (1.57)^{a}	0.00 (0.11)^{g}
T_{15}	900 W, 90 s	100.00 (1.57)^{a}	0.00 (0.11)^{g}
T_{16}	Control	0.00 (0.11)^{g}	100.00 (1.51)^{a}
SEm (±)		**0.024**	**0.01**
CD (0.05%)		**0.094**	**0.042**
CV (%)		**3.587**	**3.72**

** Angular transformed values

In each column, values with similar alphabet do not vary significantly at p=0.05

declined sharply from 76.66% at 180 W for 30 s to 16.33% at 360 W for 30 s and 11.67% at 540 W for 30 s, with complete inhibition (0%) achieved at 720 W for 30 s and all treatments exposed for 60 and 90 s (Table 2). Larval mortality increased from 11.66% at 180 W for 30 s to 63.33% at 360 W for 30 s, reaching 100% at 540 W for 30 s (Table 3) and higher treatment combinations. In contrast, pupae were comparatively tolerant, recording only 11.66% mortality at 180 W for 30 s and 81.66% even at 900 W for 30 s, while complete mortality was achieved only at 540 W for 60 s and 360 W for 90 s (Table 4). Adult mortality also increased progressively from 6.67% at 180 W for 30 s to 100% at 900 W for 30 s (Table 5).

The greater susceptibility of eggs and larvae may be attributed to their thin protective covering, higher moisture content and intense metabolic activity, which facilitate rapid absorption of microwave energy and extensive thermal injury. Conversely, the comparatively lower susceptibility of pupae is likely associated with reduced metabolic activity, lower free water content and a compact body structure that limits heat transfer. Consequently, higher microwave power and longer exposure durations were required to achieve complete mortality in the pupal stage. Similar stage-dependent susceptibility has been reported by Tayeb *et al*. (2018), who identified pupae as the least susceptible developmental stage based on higher LT_{50} values. Patil *et al*. (2020) also observed that complete mortality of pupae required 600 W for 60 s, whereas larvae and adults were controlled at lower microwave doses. Likewise, Raju *et al*. (2023) reported eggs as the most susceptible stage, with complete mortality achieved at 800 W, supporting the present findings.

Table 2. Evaluation of microwave treatments against the egg stage of *T. castaneum*

Tr. No.	Power level (Watts), Time (Seconds)	Inviable eggs (%)	Adult emergence (%)
T_1	180 W, 30 s	76.66 (61.14)^{b}	23.33 (28.85)^{d}
T_2	360 W, 30 s	16.33 (24.05)^{c}	81.66 (64.81)^{c}
T_3	540 W, 30 s	11.67 (19.88)^{d}	88.33 (70.11)^{b}
T_4	720 W, 30 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_5	900 W, 30 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_6	180 W, 60 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_7	360 W, 60 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_8	540 W, 60 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_9	720 W, 60 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_{10}	900 W, 60 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_{11}	180 W, 90 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_{12}	360 W, 90 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_{13}	540 W, 90 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_{14}	720 W, 90 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_{15}	900 W, 90 s	0.00 (0.01)^{e}	100.00 (90.00)^{a}
T_{16}	Control	100.00 (90.00)^{a}	0.00 (0.01)^{e}
SEm (±)		**0.559**	**0.758**
CD (0.05%)		**1.611**	**2.184**
CV (%)		**7.936**	**1.689**

Table 3. Effect of microwave treatments against larval stage of *T. castaneum*

Tr. No.	Power level (Watts), Time (Seconds)	Larval mortality (%) **	Adult emergence (%)**
T_1	180 W, 30 s	11.66 (19.88)^{e}	88.33 (70.11)^{b}
T_2	360 W, 30 s	63.33 (52.74)^{d}	36.66 (37.26)^{c}
T_3	540 W, 30 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_4	720 W, 30 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_5	900 W, 30 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_6	180 W, 60 s	73.33 (58.93)^{c}	26.66 (31.07)^{d}
T_7	360 W, 60 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_8	540 W, 60 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_9	720 W, 60 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_{10}	900 W, 60 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_{11}	180 W, 90 s	83.33 (65.95)^{b}	16.66 (24.05)^{e}
T_{12}	360 W, 90 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_{13}	540 W, 90 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_{14}	720 W, 90 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_{15}	900 W, 90 s	100.00 (90.00)^{a}	0.00 (0.01)^{g}
T_{16}	Control	0.00 (0.01)^{f}	100.00 (90.00)^{a}
SEm (±)		**0.603**	**0.559**
CD (0.05%)		**1.736**	**1.611**
CV (%)		**1.406**	**7.936**

Table 4. Evaluation of microwave treatments against the pupal stage of *T. castaneum*

Tr. No.	Power level (Watts), Time (Seconds)	Pupal mortality (%)**	Adult emergence (%)**
T_1	180 W, 30 s	11.66(19.88)^{g}	88.33(70.11)^{b}
T_2	360 W, 30 s	33.33(35.25)^{f}	66.66(54.75)^{c}
T_3	540 W, 30 s	28.33(32.14)^{f}	71.66(57.86)^{c}
T_4	720 W, 30 s	68.33(55.77)^{d}	31.66(34.23)^{e}
T_5	900 W, 30 s	81.66(64.69)^{c}	18.33(25.30)^{f}
T_6	180 W, 60 s	43.33(41.15)^{e}	56.66(48.84)^{d}
T_7	360 W, 60 s	90.00(1.25)^{b}	10.00(18.05)^{g}
T_8	540 W, 60 s	100.00(90.00)^{a}	0.00 (0.01)^{h}
T_9	720 W, 60 s	100.00(90.00)^{a}	0.00 (0.01)^{h}
T_{10}	900 W, 60 s	100.00(90.00)^{a}	0.00 (0.01)^{h}
T_{11}	180 W, 90 s	65.00(53.81)^{d}	35.00(36.18)^{e}
T_{12}	360 W, 90 s	100.00(90.00)^{a}	0.00 (0.01)^{h}
T_{13}	540 W, 90 s	100.00(90.00)^{a}	0.00 (0.01)^{h}
T_{14}	720 W, 90 s	100.00(90.00)^{a}	0.00 (0.01)^{h}
T_{15}	900 W, 90 s	100.00(90.00)^{a}	0.00 (0.01)^{h}
T_{16}	Control	100.00(90.00)^{a}	100(90.00)^{a}
SEm (±)		**1.313**	**0.559**
CD (0.05%)		**3.784**	**1.611**
CV (%)		**3.623**	**7.936**

Table 5. Evaluation of microwave treatments against the adult stage of *T. castaneum*

Tr. No.	Power level (Watts), Time (Seconds)	Adult mortality (%)**	Progeny adult emergence (%)**
T_1	180 W, 30 s	6.67 (12.29)^{e}	78.65 (62.54)^{b}
T_2	360 W, 30 s	23.33 (28.78)^{d}	58.99 (50.18)^{c}
T_3	540 W, 30 s	43.33 (41.15)^{c}	41.01 (39.83)^{d}
T_4	720 W, 30 s	73.33 (59.00)^{b}	29.77 (33.05)^{e}
T_5	900 W, 30 s	100.00 (90.00)^{a}	0.00(0.01)^{h}
T_6	180 W, 60 s	20.00 (26.56)^{d}	67.98 (55.59)^{c}
T_7	360 W, 60 s	73.33 (59.00)^{b}	21.35 (27.51)^{e}
T_8	540 W, 60 s	100.00 (90.00)^{a}	0.00(0.01)^{h}
T_9	720 W, 60 s	100.00 (90.00)^{a}	0.00(0.01)^{h}
T_{10}	900 W, 60 s	100.00 (90.00)^{a}	0.00(0.01)^{h}
T_{11}	180 W, 90 s	100.00 (90.00)^{a}	0.00(0.01)^{h}
T_{12}	360 W, 90 s	100.00 (90.00)^{a}	0.00(0.01)^{h}
T_{13}	540 W, 90 s	100.00 (90.00)^{a}	0.00(0.01)^{h}
T_{14}	720 W, 90 s	100.00 (90.00)^{a}	0.00(0.01)^{h}
T_{15}	900 W, 90 s	100.00 (90.00)^{a}	0.00(0.01)^{h}
T_{16}	Control	0.00 (0.01)^{f}	100.00(90.00)^{a}
SEm(±)		**1.873**	**0.529**
CD (0.05%)		**5.395**	**1.524**
CV (%)		**5.006**	**4.087**

** Angular transformed values

In each column, values with similar alphabet do not vary significantly at p=0.05

CONCLUSION

Microwave irradiation proved to be an effective non-chemical method for managing *T. castaneum* in stored rice. Insect mortality increased significantly with increasing microwave power and exposure duration, while adult emergence decreased correspondingly. Complete control of pre-infested grains was achieved at **900 W for 30 s**, **e"540 W for 60 s**, and all treatments exposed for **90 s**. Among the developmental stages, eggs were the most susceptible, followed by larvae, adults and pupae. Therefore, microwave technology has considerable potential as an environmentally safe and residue-free alternative or complementary strategy for the sustainable management of *T. castaneum* in stored grains.

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