Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Green Disinfestation Strategies for Different Stored Grains: Microwave, Infrared and Ultrasound Inactivation of the Red Flour Beetle (*Tribolium castaneum* Herbst)

Ali YILMAZ

resmialiyilmaz@gmail.com

Gaziantep University

Mustafa Bayram

Gaziantep University

Research Article

Keywords: Red Flour Beetle, Non-chemical disinfestation, Grain quality, Stored-grain pest management, Food safety

Posted Date: September 30th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10829828/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: No competing interests reported.

Abstract

Insect infestation significantly contributes to postharvest losses in stored grains worldwide, with the red flour beetle (*Tribolium castaneum)* identified as a major pest. Conventional chemical fumigants face increasing restrictions due to resistance development and environmental concerns, necessitating alternative physical control methods. This study evaluated the efficacy of microwave (MW), infrared (IR) and ultrasound (US) treatments against adult the red flour beetle across five grain types: wheat, bulgur, buckwheat, lentil and chickpea. MW treatments (360–900 W, 10–40 s) achieved 85–100% mortality, with temperature increase (50–90°C) and exposure time strongly correlating with insect inactivation ($r = 0.76–0.85$, $p < 0.01$) and moisture reduction ($r = -0.38$, $p < 0.05$). IR exposure (50–90°C, 180–300 s) resulted in 80–98% mortality, with moderate negative correlations between moisture content and exposure ($r = -0.50$, $p < 0.01$) and minimal effects on color ($\Delta E < 2.5$). US treatment (100 kW, 50–90°C, 600–1800 s) relied on combined mechanical and thermal effects, yielding 70–95% mortality depending on grain type, with higher efficacy in smaller, low-density grains. Pearson correlation analyses and hierarchical cluster analysis revealed that temperature, exposure time and grain physicochemical properties (moisture, starch and protein content) were critical determinants of insect mortality across treatments. Grain-specific differences indicated that buckwheat and lentil absorbed MW and IR energy more efficiently, resulting in faster mortality, whereas wheat and chickpea required longer exposure. Collectively, all three physical methods achieved near-complete the red flour beetle control under optimized conditions, with MW providing rapid insect inactivation, IR enabling uniform thermal distribution and US preserving grain quality. These findings support the potential of MW, IR and US as residue-free, sustainable strategies for stored-grain pest management and emphasize the importance of tailoring treatment parameters to grain type and physicochemical properties.

1. Introduction

Stored-grain losses due to insect infestations continue to represent one of the most persistent challenges in global food security, with significant implications for both yield and quality of cereals, pulses and other stored commodities. Post-harvest deterioration, caused by biological agents including insects, mites, rodents and microorganisms, has remained a critical bottleneck despite substantial advancements in agricultural production technologies. Globally, post-harvest losses attributable to these biotic factors are estimated at approximately 10%, with insects alone responsible for nearly half of that figure, accounting for around 5% of total losses (Hodges et al., 2014). Such losses are not evenly distributed: developed countries typically report lower loss levels, ranging between 1% and 10%, while developing regions often experience significantly higher rates, frequently reaching 10–30% of stored commodities (Phillips and Throne, 2010). The severity of post-harvest losses is particularly pronounced in tropical and subtropical climates, where high temperatures and humidity create optimal conditions for rapid insect development and reproduction. In India, for example, economic damages attributed to stored-grain insects have been estimated to reach several billion dollars annually (Boxall, 2002). The impact of insect infestation extends beyond quantitative grain loss; qualitative deterioration is equally important. Infested grains often exhibit changes in color, odor, flavor and nutritional composition and are frequently contaminated with insect fragments and excreta. These alterations not only reduce market value but can also pose significant health risks, including allergenic reactions and microbial contamination (Athanassiou et al., 2019). The multifaceted consequences of insect infestations underscore the urgent need for effective, sustainable and safe pest control strategies in stored-grain management. Among the many insect species that infest stored grains, the red flour beetle (*Tribolium castaneum* Herbst) is particularly significant due to its wide

distribution and economic impact (Mydeen et al., 2025). This secondary pest predominantly attacks processed and broken grain fractions but is highly adaptable to various storage conditions. Over time, populations of the red flour beetle have been reported to develop resistance to multiple insecticidal agents, posing a formidable challenge to chemical-based pest control (Athanassiou et al., 2019). Its rapid reproductive cycle, tolerance to adverse environmental conditions and genetic plasticity make it an ideal model species for evaluating novel disinfestation technologies. The emergence of resistance against conventional fumigants, including phosphine and pyrethroids, has become a major concern for long-term pest management in stored-grain systems worldwide (Fields and White, 2002).

1.1 Limitations of Conventional Chemical Control

Historically, chemical fumigation and contact insecticides have been the cornerstone of stored-grain pest management strategies. Synthetic agents such as phosphine, methyl bromide and pyrethroids have been widely applied due to their proven efficacy and cost-effectiveness. However, the extensive reliance on chemical control methods has increasingly been questioned, owing to several critical limitations: environmental impact, human health concerns, pest resistance and trade restrictions associated with chemical residues. The phase-out of methyl bromide under the Montreal Protocol on Substances that Deplete the Ozone Layer provides a clear example of how environmental regulations have reshaped pest control practices in the food industry (Fields and White, 2002). Although phosphine remains one of the most commonly used fumigants due to its low cost and penetrative ability, its efficacy has been significantly compromised in many regions by the development of resistant insect populations. In addition, residues from synthetic insecticides can negatively affect consumer safety and limit the export potential of treated grains, particularly given increasingly stringent maximum residue limits (MRLs) set by international food safety regulations (Hashem et al., 2025). Collectively, these challenges emphasize the urgent need for alternative pest management strategies that are safe, sustainable and free of chemical residues.

1.2 Emergence of Non-Chemical Physical Control Methods

In response to the limitations of chemical fumigation, considerable research attention has turned to physical and non-chemical disinfestation techniques. These approaches are designed to inactivate insect pests while preserving the intrinsic quality of the stored grains. Physical disinfestation methods leverage various mechanisms—including thermal, mechanical and acoustic energy—to disrupt insect physiology without introducing chemical residues (Mariadoss et al., 2025). Among these, dielectric heating technologies—particularly microwave (MW) and radio-frequency (RF) treatments—have garnered significant attention. These methods rely on volumetric heating, which increases the temperature of grains and insects simultaneously through electromagnetic interaction with polar molecules, primarily water. This volumetric heating mechanism contrasts with conventional conduction or convection heating, offering faster, more uniform treatment (Nelson, 1996; Vadivambal and Jayas, 2010).

Microwave treatment has demonstrated notable efficacy in inactivating stored-product insects across a range of grains, including rice, wheat, pulses and processed flour. Advantages of MW treatment include rapid heating, short exposure times, energy efficiency and the absence of chemical residues. Furthermore, when appropriately optimized, MW treatment can maintain or even enhance certain physicochemical properties of grains, including moisture content, protein integrity and carbohydrate composition (Kumar et al., 2019). The key challenge lies in balancing insect mortality with minimal alterations to grain quality, which requires precise control of exposure

duration, power intensity and grain mass. Infrared (IR) irradiation represents another thermally based non-chemical approach, operating within the 0.78–1000 μm wavelength range to achieve surface and near-surface heating. Historically applied for drying and roasting operations, IR radiation has shown promise as an insect disinfestation tool. The efficacy of IR treatment depends on parameters such as radiation intensity, exposure time and the distance between the IR source and grain surface. Optimization is critical to prevent excessive heating, which can adversely affect grain color, texture and nutritional quality (Mahroof et al., 2003; Subramanyam and Mahroof, 2014). Acoustic and ultrasonic (US) technologies offer a distinct, non-thermal approach to insect management. Acoustic energy, particularly in the ultrasonic range (> 20 kHz), has been employed primarily for insect detection and monitoring, exploiting vibrations generated by insect movement or feeding within grain masses (Mankin et al., 2011; Herrick and Mankin, 2012). High-intensity ultrasound has more recently been investigated as a potential disinfestation tool, capable of inducing insect mortality via mechanical vibration, cavitation and cellular disruption (Ikediala et al., 1999). While US treatment is less mature than MW or IR techniques, its non-thermal and residue-free nature makes it an attractive candidate for further research.

1.3 Quality Considerations in Physical Disinfestation

The practical adoption of non-chemical disinfestation methods hinges not only on their efficacy in eliminating pests but also on their ability to preserve grain quality. Thermal treatments—MW and IR in particular—carry inherent risks of altering key quality attributes, including moisture content, color, flavor and protein functionality. Such alterations can compromise both the market value and consumer acceptability of treated grains. Moisture content is a critical parameter, influencing not only the storability of grains but also the effectiveness of disinfestation treatments (Hardy et al., 1999; Anumudu et al., 2024). Excessive drying can result in kernel shrinkage, textural changes and increased susceptibility to breakage. Color attributes, quantified using the L*, a*, b* system along with derived metrics such as yellowness index (YI) and total color difference (ΔE), serve as sensitive indicators of chemical and structural changes. Shifts in these parameters may reflect Maillard reactions, pigment degradation or oxidative browning, which impact both visual appeal and nutritional quality (Bassey et al., 2013). Comprehensive evaluation of these indicators alongside insect mortality is essential for determining the feasibility and commercial viability of MW, IR and US treatments. The intrinsic physical properties of grains—kernel size, density, surface roughness and initial moisture content—also play a critical role in treatment outcomes. For instance, smaller or more porous kernels may absorb electromagnetic energy more rapidly, resulting in uneven heating or localized overexposure. Similarly, the texture and composition of different legumes, such as lentils and chickpeas, can influence heat transfer and acoustic energy propagation, thereby affecting insect mortality and quality outcomes (Fakude, 2009; Vadivambal et al., 2008).

1.4 Need for Comparative and Quantitative Evaluations

Although individual studies on MW, IR and US treatments have achieved significant progress, comparative investigations across different grain types under standardized conditions remain quite limited and this gap hinders a comprehensive understanding of how structural and compositional differences among grains affect treatment efficacy. Most existing literature primarily focuses on insect mortality, while studies systematically and quantitatively assessing the impact of these treatments on grain quality are relatively rare, which complicates the development of reliable, grain-specific application protocols (Srivastava and Mishra, 2021; Ouaarous et al., 2025). Evaluating parameters such as moisture content, color changes, structural integrity and other quality attributes alongside insect mortality allows for the identification of optimal conditions that ensure effective pest control while preserving processability, shelf life and consumer acceptance, which is especially

critical in understanding the variations in energy absorption and heat transfer among different grain types (Sadekla et al., 2025). This approach has been particularly underexplored for diverse grains such as wheat, bulgur, buckwheat, lentils and chickpeas in relation to the red flour beetle, with most studies focusing on a single grain type or a limited set of quality parameters. Grain-specific characteristics can significantly influence energy absorption, heat transfer and acoustic propagation, thereby markedly affecting treatment efficacy and insect mortality outcomes.

1.5 Objectives of the Study

In light of gaps in the literature, this study was designed to comprehensively evaluate non-chemical physical disinfestation techniques against the red flour beetle. The specific objectives are:

1. To assess the inactivation efficiency of the red flour beetle adults across five grain types—wheat, bulgur, buckwheat, lentil and chickpea—using three physical treatments: MW, IR and US.
2. To quantify treatment-induced changes in key grain quality attributes, including moisture content and color difference (ΔE), as indicators of post-treatment quality and consumer acceptability.
3. To develop and compare multiple regression models—including Linear, Quadratic and Two-Factor Interaction (2FI) models—using SPSS and Design Expert, in order to elucidate the quantitative relationships between insect mortality and grain quality changes and to predict the balance between disinfestation efficacy and product preservation across different treatments and grain types.

By achieving these objectives, the study provides a holistic, comparative and quantitatively grounded framework for evaluating non-chemical disinfestation technologies in stored grains. The findings are expected to support the development of sustainable, residue-free and energy-efficient pest control strategies that ensure safe and high-quality food

2. Materials and Methods

2.1. Materials

2.1.1. Insect Species

The insect species used in this study was the red flour beetle (*Tribolium castaneum*), one of the most common pests of stored food products. The insects were obtained from laboratory cultures maintained at the Department of Agricultural Engineering, Kahramanmaraş Sütçü İmam University (Kahramanmaraş, Türkiye). Cultures were kept under controlled environmental conditions of 28 ± 2°C and 65 ± 5% relative humidity (RH), which simulate typical storage environments and ensure optimal development. Only healthy adult individuals of similar physiological age and activity levels were selected for the experiments to ensure consistency. The species was used to evaluate both behavioral preferences for different grain types and the subsequent biochemical impact on grain quality following prolonged exposure.

2.1.2. Grain Samples

Grain samples, including wheat (*Triticum aestivum*), bulgur (processed wheat), buckwheat (*Fagopyrum esculentum*), lentils (*Lens culinaris*) and chickpeas (*Cicer arietinum*), were obtained from the same commercial brand to ensure consistency and minimize variability across experimental units. The grains were purchased from

a local market in Gaziantep, Türkiye and stored under standard laboratory conditions before the experiments. All samples were visually inspected to ensure they were free from prior insect damage or mold before use. These substrates served both as food sources in the behavioural tests and as the basis for chemical composition analyses after insect exposure.

2.2. Methods

2.2.1. Experimental Design

This study was designed to evaluate the inactivation efficiency of the red flour beetle adults under different thermal and acoustic treatments (MW, IR and US) and to examine the effects of these treatments on selected grain parameters, including moisture content, color attributes and initial/final temperature changes, in five different grain types (wheat, bulgur, buckwheat, lentil and chickpea). Each experimental unit consisted of 25 g of grains containing 25 adult insects and all treatment combinations were conducted in duplicate (n = 2) to ensure reliability and reproducibility. MW treatments were applied at three power levels (300, 600 and 900 W) for six different durations (10, 20, 30, 40, 50 and 60 s), IR treatments were performed at three temperatures (50, 70 and 90°C) for 3 and 5 minutes and US treatments were conducted at a fixed power of 100 W at 50, 70 and 90°C for 10, 20 and 30 minutes. Surface temperatures of the samples were recorded before and after treatment using a laser thermometer (IR838 Laser Thermometer, Benetech, China) and insect mortality was determined immediately after treatment by counting. Also, Moisture content (Radwag MA50R Infrared Moisture Analyzer, Poland) and color attributes (Colorflex EZ, HunterLab, USA) of both insect-contact and insect-free samples were measured. Statistical analysis of moisture and color data was performed using SPSS 29.0 software (IBM Corp., NY, USA). This comprehensive experimental design enabled a detailed evaluation of both the efficacy of the applied treatments on insect inactivation and their potential impacts on grain quality parameters.

2.2.2. Moisture Content

Moisture content (MC, %) of the grain samples was determined using the oven-drying method (AOAC, 2000). In this method, a known weight of the sample was placed in a preheated oven at 135°C and dried until a constant weight was achieved. The moisture content was then calculated using the following formula:

$$\mathrm{MC}\,(\%) = \frac{\mathrm{W_i} - \mathrm{W_f}}{\mathrm{W_i}} \times\ 100$$

where $\mathrm{W_i}$= initial weight (g) of sample and $\mathrm{W_f}$= final weight (g) of sample.

2.2.3. Color Analysis

Color parameters of the grain samples were determined using a spectrophotometric colorimeter (Colorflex EZ, HunterLab, USA). Prior to measurement, the instrument was calibrated according to the manufacturer's instructions using the standard white and black calibration tiles provided. For each sample, grains were evenly spread in a petri dish to create a uniform surface for measurement. The L* (lightness), a* (red-green) and b* (yellow-blue) values were recorded under standard illuminant D65 and 10° observer conditions. Three measurements were taken at different positions for each sample to account for surface heterogeneity and the average of these readings was reported as the representative color value. The total color difference (ΔE) was calculated as:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2}$$

where L_0^*, a_0^* and b_0^* are initial values and L^*, a^* and b^* are measured values.

2.2.4. Insect Mortality Assessment

Adult the red flour beetles were exposed to three different physical treatments — MW, IR and US — using the experimental setups illustrated in Fig. 1. All experiments were performed with five grain types (buckwheat, bulgur, chickpea, lentil and wheat) to assess the influence of substrate characteristics on insect inactivation efficiency. Each treatment × grain combination was replicated three times.

Microwave treatment

Microwave exposures were conducted at 360, 600 and 900 W power levels for 10, 20, 30 and 40 s. Petri dishes containing insects and grain samples were covered with gauze and secured with a rubber band before being placed in the microwave chamber (see Fig. 1a).

Infrared treatment

Infrared inactivation experiments were performed using an IR heating device equipped with controlled wavelength emission. Three dominant wavelengths (360, 600 and 900 nm) and four exposure durations (10, 20, 30 and 40 s) were applied. Samples were placed in Petri dishes under an IR radiator and covered with gauze to ensure uniform heating (Fig. 1b). The surface temperature of grains was monitored with a thermocouple to prevent overheating.

Ultrasound treatment

Ultrasound treatments were carried out using an ultrasonic bath operating at 40 kHz. Grain samples containing adult insects were sealed in ziplock bags, submerged in the bath and weighted with a glass plate (Fig. 1c). Three bath temperatures (50, 70 and 90°C) and three exposure times (600, 1200 and 1800 s) were tested.

Observed mortality (%) was calculated as the number of dead insects divided by the initial number of live insects, multiplied by 100:

$$\text{Observed mortality (\%)} = \frac{\text{Number of dead insects}}{\text{Initial number of live insects}} \times 100$$

2.2.5. Treatment Application and Measurement Procedure

All treatments were performed sequentially for each grain type following the experimental design matrix. For each run, 25 g of grain samples containing 25 adult the red flour beetle were placed in glass containers and subjected to the assigned treatment (MW, IR or US) under controlled conditions. After treatment, the samples were immediately cooled to room temperature (25 ± 1°C) to prevent post-exposure thermal effects. Insect mortality was recorded immediately, while treated grains were subsequently analyzed for moisture content and color parameters as described in Sections 2.2.2 and 2.2.3. Control samples (untreated) were maintained under

identical environmental conditions to serve as reference data. All experiments were conducted in duplicate and data were expressed as mean ± standard deviation.

2.6. Statistical Analysis

2.6.1. SPSS-Based Statistical Analysis

All experimental data were initially summarized using descriptive statistics, including means, standard deviations and percentages, to provide an overall characterization of the observed outcomes. Relationships between continuous variables were evaluated using Pearson correlation analysis to measure the strength and direction of linear associations. To explore patterns and relationships within the dataset, a matrix-cluster analysis was conducted, allowing for classification and grouping of similar observations based on multiple variables. All statistical analyses and modeling procedures were performed using SPSS software (version 26, IBM, USA), with significance levels set at $p < 0.05$.

2.6.2. Design-Expert Modeling and Response Surface Analysis

In addition to conventional statistical analyses, Design-Expert software (Version 13, Stat-Ease Inc., Minneapolis, MN, USA) was employed to perform regression modeling and response surface methodology (RSM). The models were developed to describe the combined effects of treatment temperature and exposure time on the measured responses, including insect mortality, color difference (ΔE) and moisture content. Analysis of variance (ANOVA) was used to evaluate the significance of each model and its terms. Model adequacy was assessed based on the coefficient of determination (R^2), adjusted R^2, predicted R^2 and lack-of-fit tests. Three-dimensional (3D) response surface plots were generated to visualize the interaction effects of the independent variables on each response. Optimization was conducted using the desirability function approach to determine the best parameter combination yielding maximum mortality and minimum quality loss.

3. Result

The control of stored-product pests through physical treatments, such as MW, IR and US, has gained attention as a chemical-free and environmentally friendly alternative to conventional fumigation methods. These treatments rely on energy transfer to inactivate insects by inducing thermal or mechanical stress, thereby preventing postharvest losses and maintaining the quality of grains and legumes. Among the most common pests in stored cereals and legumes, the red flour beetle poses a significant threat due to its high reproductive rate, feeding activity and adaptability to various grain matrices. In this study, the effects of MW, IR and US treatments on red flour beetle mortality, moisture content, temperature differences and color variation were systematically evaluated across five grain types: wheat, bulgur, buckwheat, lentil and chickpea. The results provide insights into the relationships between processing parameters, grain type and pest inactivation efficiency, offering guidance for the optimization of non-chemical disinfestation methods.

3.1 Effects of Microwave Exposure

MW treatment significantly influenced red flour beetle mortality, grain temperature, moisture content and color difference, with trends varying according to power, exposure time and grain type (Table 1, Fig. 3). Increasing microwave power from 360 to 900 nm and prolonging exposure times from 10 to 40 seconds directly enhanced insect mortality. For instance, in buckwheat, mortality increased from 44.00% at 360 nm and 10 s to 100% at 30

s. At 600 nm, mortality similarly rose from 56.00% to 100% over the same time range. These results indicate a clear relationship between microwave energy input and insect lethality. Among the grains tested, bulgur and wheat showed the highest temperature differences (107.30°C and 92.15°C at 900 nm for 40 s), corresponding to complete insect inactivation. In contrast, chickpea and lentil exhibited slightly lower temperature increases (82.20°C and 76.10°C) but still achieved 100% mortality, suggesting that grain composition and moisture content modulate heat transfer efficiency. Moisture content generally decreased with increasing microwave power and exposure time, reflecting evaporative effects associated with volumetric heating. For example, wheat moisture decreased from 10.34% at 360 nm and 10 s to 8.51% at 40 s, while bulgur moisture dropped from 8.54% to 5.16% under the 900 nm, 10–40 s treatments. Color difference (ΔE) increased slightly with prolonged exposure, rising from 44.74 to 46.83 in buckwheat and from 68.89 to 75.02 in wheat, indicating minor surface darkening or pigment degradation without substantial visual quality loss. The response surfaces (Fig. 3) illustrate that longer exposure times and shorter wavelengths are associated with higher surface temperatures and more pronounced color changes, reflecting more intense energy absorption and localized heating. Wheat and bulgur exhibited relatively smooth response surfaces, indicating stable heat distribution, while buckwheat and lentil showed steeper surfaces, suggesting greater sensitivity to microwave energy due to differences in size, density and water retention capacity. Chickpea showed moderate responses, with less pronounced variations. These findings confirm that MW treatment can achieve rapid and complete red flour beetle inactivation, but careful parameter optimization is required to minimize quality changes (Table 1, Fig. 3).
Pearson correlation analysis further supported these observations (Table 4). Wavelength showed a weak but significant positive correlation with temperature difference ($r = 0.267$, $p < 0.01$) and mortality ($r = 0.210$, $p < 0.05$) and a moderate negative correlation with moisture content ($r = -0.382$, $p < 0.01$), indicating that longer wavelengths slightly increase heating and insect mortality while reducing grain moisture. Exposure time was strongly positively correlated with temperature difference ($r = 0.894$, $p < 0.01$) and mortality ($r = 0.736$, $p < 0.01$) and strongly negatively correlated with moisture content ($r = -0.664$, $p < 0.01$), showing that longer MW exposure significantly enhances heating and insect mortality while lowering moisture content. Temperature difference was moderately positively correlated with mortality ($r = 0.640$, $p < 0.01$) and strongly negatively correlated with moisture content ($r = -0.726$, $p < 0.01$), confirming that higher heating leads to greater mortality and reduced moisture. Mortality was also negatively correlated with moisture content ($r = -0.606$, $p < 0.01$), highlighting that drier grains result in higher insect death. Color difference (ΔE) showed no significant correlation with any parameter ($p > 0.05$), indicating minimal effect of MW treatment on grain appearance.

Table 1
Effects of microwave (MW) exposure on the red flour beetle in different grain types

Grain	Wavelenght	Time (sec)	Moisture Content	Mortality	Temperature Difference	Color Difference
	nm		(%)	(%)	(°C)	(ΔE)
Buckwheat	360	10	9.17 ± 0.69^{AAa}	44.00 ± 5.66^{AAa}	14.85 ± 1.77^{AAa}	44.74 ± 0.14^{AAa}
		20	9.00 ± 0.16^{AAb}	90.00 ± 2.83^{AAb}	25.80 ± 3.96^{AAb}	45.71 ± 0.40^{AAb}
		30	9.11 ± 0.25^{AAc}	100.00 ± 0.00^{AAc}	43.90 ± 6.65^{AAc}	45.26 ± 0.01^{AAc}
		40	8.52 ± 1.26^{AAd}	100.00 ± 0.00^{AAd}	62.05 ± 3.32^{AAd}	46.83 ± 0.06^{AAd}
	600	10	9.19 ± 0.60^{ABa}	56.00 ± 0.00^{ABa}	19.20 ± 1.56^{ABa}	46.83 ± 0.04^{ABa}
		20	7.94 ± 1.15^{ABb}	98.00 ± 2.83^{ABb}	40.85 ± 4.74^{ABb}	45.69 ± 0.01^{ABb}
		30	6.82 ± 0.96^{ABc}	100.00 ± 0.00^{ABc}	54.25 ± 2.19^{ABc}	47.19 ± 0.10^{ABc}
		40	7.34 ± 1.99^{ABd}	100.00 ± 0.00^{ABd}	77.80 ± 10.18^{ABd}	45.88 ± 0.24^{ABd}
	900	10	8.96 ± 0.25^{ACa}	76.00 ± 11.31^{ACa}	22.70 ± 4.67^{ACa}	45.26 ± 0.12^{ACa}
		20	7.46 ± 0.17^{ACb}	100.00 ± 0.00^{ACb}	33.40 ± 2.12^{ACb}	46.10 ± 0.10^{ACb}
		30	6.73 ± 1.35^{ACc}	100.00 ± 0.00^{ACc}	61.55 ± 14.21^{ACc}	45.98 ± 0.21^{ACc}
		40	6.83 ± 0.11^{ACd}	100.00 ± 0.00^{ACd}	86.75 ± 13.65^{ACd}	44.93 ± 0.00^{ACd}
Bulgur	360	10	10.28 ± 0.11^{BCa}	44.00 ± 5.66^{BCa}	24.25 ± 0.78^{BCa}	64.75 ± 0.10^{BCa}
		20	9.24 ± 0.86^{BCb}	96.00 ± 0.00^{BCb}	32.05 ± 1.48^{BCb}	64.06 ± 0.30^{BCb}
		30	9.39 ± 0.39^{BCc}	100.00 ± 0.00^{BCc}	48.40 ± 2.69^{BCc}	63.75 ± 0.29^{BCc}
		40	5.76 ± 0.40^{BCd}	100.00 ± 0.00^{BCd}	58.00 ± 0.42^{BCd}	63.95 ± 0.30^{BCd}

	600	10	9.22 ± 0.53^{BBa}	52.00 ± 5.66^{BBa}	28.55 ± 0.78^{BBa}	65.43 ± 0.33^{BBa}
		20	6.78 ± 0.55^{BBb}	100.00 ± 0.00^{BBb}	39.15 ± 1.06^{BBb}	64.09 ± 0.20^{BBb}
		30	6.82 ± 0.41^{BBc}	100.00 ± 0.00^{BBc}	67.85 ± 5.30^{BBc}	61.30 ± 6.46^{BBc}
		40	5.04 ± 0.39^{BBd}	100.00 ± 0.00^{BBd}	100.95 ± 4.60^{BBd}	64.83 ± 0.05^{BBd}
	900	10	8.54 ± 0.23^{BCa}	60.00 ± 11.31^{BCa}	31.15 ± 0.92^{BCa}	65.28 ± 0.04^{BCa}
		20	6.43 ± 0.11^{BCb}	100.00 ± 0.00^{BCb}	42.35 ± 0.49^{BCb}	64.84 ± 0.10^{BCb}
		30	6.45 ± 0.12^{BCc}	100.00 ± 0.00^{BCc}	70.40 ± 3.54^{BCc}	65.41 ± 0.06^{BCc}
		40	5.16 ± 0.26^{BCd}	100.00 ± 0.00^{BCd}	107.30 ± 6.79^{BCd}	55.56 ± 16.69^{BCd}
Chickpea	360	10	11.18 ± 0.06^{BAa}	60.00 ± 5.66^{BAa}	8.70 ± 0.42^{BAa}	61.05 ± 0.23^{BAa}
		20	9.92 ± 0.09^{BAb}	76.00 ± 5.66^{BAb}	23.05 ± 1.91^{BAb}	61.27 ± 0.28^{BAb}
		30	8.32 ± 0.76^{BAc}	86.00 ± 8.49^{BAc}	34.55 ± 4.03^{BAc}	63.20 ± 0.08^{BAc}
		40	7.77 ± 0.64^{BAd}	98.00 ± 2.83^{BAd}	71.35 ± 8.56^{BAd}	62.04 ± 0.30^{BAd}
	600	10	10.42 ± 0.35^{BBa}	68.00 ± 5.66^{BBa}	12.05 ± 0.07^{BBa}	62.07 ± 0.16^{BBa}
		20	8.55 ± 0.49^{BBb}	84.00 ± 11.31^{BBb}	28.25 ± 3.32^{BBb}	60.81 ± 0.21^{BBb}
		30	6.95 ± 0.17^{BBc}	100.00 ± 0.00^{BBc}	45.25 ± 4.31^{BBc}	61.22 ± 0.08^{BBc}
		40	6.66 ± 0.12^{BBd}	100.00 ± 0.00^{BBd}	82.20 ± 12.30^{BBd}	60.81 ± 0.54^{BBd}
	900	10	9.74 ± 1.18^{BCa}	92.00 ± 0.00^{BCa}	14.35 ± 0.78^{BCa}	61.17 ± 0.33^{BCa}
		20	8.71 ± 2.67^{BCb}	100.00 ± 0.00^{BCb}	38.30 ± 2.55^{BCb}	61.03 ± 0.05^{BCb}
		30	7.63 ± 2.29^{BCc}	100.00 ± 0.00^{BCc}	71.75 ± 13.65^{BCc}	62.19 ± 0.02^{BCc}

		40	7.73 ± 0.78^{BCd}	100.00 ± 0.00^{BCd}	76.10 ± 1.84^{BCd}	60.81 ± 0.13^{BCd}
Lentil	360	10	9.91 ± 0.01^{BCa}	40.00 ± 5.66^{BCa}	8.70 ± 0.42^{BCa}	73.41 ± 0.06^{BCa}
		20	8.38 ± 0.36^{BCb}	98.00 ± 2.83^{BCb}	23.05 ± 1.91^{BCb}	72.85 ± 0.05^{BCb}
		30	7.68 ± 0.76^{BCc}	100.00 ± 0.00^{BCc}	34.55 ± 4.03^{BCc}	72.03 ± 0.04^{BCc}
		40	7.11 ± 0.29^{BCd}	100.00 ± 0.00^{BCd}	71.35 ± 8.56^{BCd}	72.83 ± 0.02^{BCd}
	600	10	9.57 ± 0.09^{BBa}	60.00 ± 0.00^{BBa}	12.05 ± 0.07^{BBa}	72.35 ± 0.02^{BBa}
		20	8.53 ± 0.79^{BBb}	100.00 ± 0.00^{BBb}	28.25 ± 3.32^{BBb}	72.18 ± 0.06^{BBb}
		30	6.98 ± 1.26^{BBc}	100.00 ± 0.00^{BBc}	45.25 ± 4.31^{BBc}	71.03 ± 0.04^{BBc}
		40	5.96 ± 0.84^{BBd}	100.00 ± 0.00^{BBd}	82.20 ± 12.30^{BBd}	72.42 ± 0.04^{BBd}
	900	10	8.73 ± 0.28^{BCa}	76.00 ± 0.00^{BCa}	14.35 ± 0.78^{BCa}	72.41 ± 0.29^{BCa}
		20	7.51 ± 0.21^{BCb}	100.00 ± 0.00^{BCb}	38.30 ± 2.55^{BCb}	71.69 ± 0.04^{BCb}
		30	6.67 ± 0.95^{BCc}	100.00 ± 0.00^{BCc}	71.75 ± 13.65^{BCc}	71.42 ± 0.07^{BCc}
		40	6.40 ± 0.38^{BCd}	100.00 ± 0.00^{BCd}	76.10 ± 1.84^{BCd}	72.39 ± 0.08^{BCd}
Wheat	360	10	10.34 ± 0.03^{CAa}	44.00 ± 5.66^{CAa}	18.15 ± 2.47^{CAa}	68.89 ± 0.25^{CAa}
		20	8.49 ± 0.01^{CAb}	98.00 ± 2.83^{CAb}	33.85 ± 5.87^{CAb}	70.36 ± 0.70^{CAb}
		30	8.63 ± 0.28^{CAc}	100.00 ± 0.00^{CAc}	49.45 ± 1.91^{CAc}	70.70 ± 0.09^{CAc}
		40	8.51 ± 0.27^{CAd}	100.00 ± 0.00^{CAd}	61.35 ± 5.73^{CAd}	71.59 ± 0.76^{CAd}
	600	10	10.09 ± 0.01^{CBa}	60.00 ± 11.31^{CBa}	21.55 ± 2.19^{CBa}	69.92 ± 0.19^{CBa}
		20	9.79 ± 0.13^{CBb}	100.00 ± 0.00^{CBb}	41.95 ± 2.33^{CBb}	72.21 ± 0.36^{CBb}

	30	8.62 ± 0.12^{CBc}	100.00 ± 0.00^{CBc}	57.65 ± 5.02^{CBc}	70.77 ± 0.18^{CBc}
	40	7.71 ± 0.81^{CBd}	100.00 ± 0.00^{CBd}	88.80 ± 1.98^{CBd}	73.56 ± 0.15^{CBd}
900	10	8.64 ± 0.59^{CCa}	64.00 ± 5.66^{CCa}	26.40 ± 1.13^{CCa}	71.02 ± 0.09^{CCa}
	20	7.21 ± 2.02^{CCb}	100.00 ± 0.00^{CCb}	43.60 ± 9.76^{CCb}	71.77 ± 0.23^{CCb}
	30	6.53 ± 1.39^{CCc}	100.00 ± 0.00^{CCc}	67.45 ± 0.07^{CCc}	73.34 ± 1.06^{CCc}
	40	5.93 ± 0.88^{CCd}	100.00 ± 0.00^{CCd}	92.15 ± 0.07^{CCd}	75.02 ± 0.02^{CCd}

3.2 Effects of Infrared Exposure

Infrared exposure demonstrated a strong influence of temperature and exposure time on red flour beetle mortality, grain moisture content and visual quality parameters (Table 2, Table 5, Fig. 4). Mortality increased sharply with rising temperature (50, 70 and 90°C) and longer exposure times (180–300 s). For example, in buckwheat, mortality remained low at 50°C (2–4%) but increased to 86% at 70°C for 240 s and reached 100% at 300 s. At 90°C, 100% mortality was achieved after 240 s, indicating a strong temperature-dependent response. Similar trends were observed in bulgur, wheat, lentil and chickpea, with full inactivation requiring higher temperatures and prolonged exposure—for instance, bulgur achieved complete mortality at 70°C for 300 s and wheat at 90°C for 240–300 s. Moisture content consistently decreased with increasing IR temperature and exposure time, indicating that water loss contributes to insect mortality. In buckwheat, moisture decreased from 8.67% at 50°C/180 s to 4.36% at 90°C/300 s, while lentil moisture dropped from 8.79% to 3.94% under similar conditions. Temperature difference (ΔT) rose substantially with increasing temperature, from 27.10°C (50°C/180 s) to 84.10°C (90°C/300 s) in buckwheat, highlighting cumulative thermal effects. Color difference (ΔE) showed minor increases in buckwheat (from 45.56 to 45.82), while ΔE in bulgur and wheat remained relatively stable (63–70), suggesting limited visual quality changes despite effective insect control. Pearson correlation analysis confirmed these observations, showing strong positive correlations between temperature and both temperature difference ($r = 0.929$, $p < 0.01$) and mortality ($r = 0.757$, $p < 0.01$), emphasizing that higher IR temperatures increase grain heating and insect inactivation. Exposure time correlated moderately with temperature difference ($r = 0.254$, $p < 0.05$) and mortality ($r = 0.395$, $p < 0.01$), but negatively with moisture content ($r = -0.789$, $p < 0.01$), indicating that prolonged IR exposure reduces moisture, further enhancing mortality. Temperature difference was positively correlated with mortality ($r = 0.840$, $p < 0.01$) and negatively with moisture content ($r = -0.679$, $p < 0.01$), confirming that cumulative heat exposure drives both inactivation and drying. Mortality and moisture content were strongly negatively correlated ($r = -0.713$, $p < 0.01$), while color difference (ΔE) showed no significant correlations ($p > 0.05$), reflecting minimal impact on visual quality. Overall, these data highlight that temperature and exposure time are primary drivers of red flour beetle mortality under IR treatment, with moisture reduction contributing and color largely unaffected (Table 2, Table 5, Fig. 4).

Table 2
Effects of infrared (IR) exposure on the red flour beetle in different grain types

Grain	Temperature (°C)	Time (sec)	Moisture Content (%)	Mortality (%)	Temperature Difference (°C)	Color Difference (ΔE)
Buckwheat	50	180	8.67 ± 0.01^{Aa}	4,00 ± 0,00^{Ab}	27.10 ± 3.54^{Ac}	45.56 ± 0.32^{Ad}
		240	8.19 ± 0.12^{Aa}	2,00 ± 2.83^{Ab}	29.10 ± 1.27^{Ac}	46.21 ± 0.04^{Ad}
		300	6.65 ± 0.27^{Aa}	4,00 ± 0,00^{Ab}	31.00 ± 1.13^{Ac}	46.38 ± 0.23^{Ad}
	70	180	7.75 ± 0.28^{Aa}	6,00 ± 2.83^{Ab}	47.45 ± 2.62^{Ac}	46.69 ± 0.08^{Ad}
		240	7.22 ± 0.16^{Aa}	86,00 ± 14.14^{Ab}	53.20 ± 1.56^{Ac}	46.45 ± 0.01^{Ad}
		300	4.96 ± 0.27^{Aa}	100,00 ± 0,00^{Ab}	59.70 ± 1.56^{Ac}	46.56 ± 0.03^{Ad}
	90	180	6.75 ± 0.02^{Aa}	78,00 ± 8.49^{Ab}	73.30 ± 2.40^{Ac}	45.58 ± 0.04^{Ad}
		240	6.54 ± 0.01^{Aa}	100,00 ± 0,00^{Ab}	78.75 ± 1.06^{Ac}	46.04 ± 0.05^{Ad}
		300	4.36 ± 0.28^{Aa}	100,00 ± 0,00^{Ab}	84.10 ± 1.70^{Ac}	45.82 ± 0.01^{Ad}
Bulgur	50	180	8.58 ± 0.25^{Ba}	8,00 ± 5.66^{Bb}	28.70 ± 0.00^{Bc}	63.43 ± 0.23^{Bd}
		240	7.34 ± 0.25^{Ba}	2,00 ± 2.83^{Bb}	32.25 ± 2.05^{Bc}	63.58 ± 0.01^{Bd}
		300	6.28 ± 0.52^{Ba}	2,00 ± 2.83^{Bb}	36.15 ± 3.04^{Bc}	64.16 ± 0.13^{Bd}
	70	180	7.36 ± 0.26^{Ba}	10,00 ± 2.83^{Bb}	51.10 ± 5.94^{Bc}	64.00 ± 0.01^{Bd}
		240	6.56 ± 0.52^{Ba}	90,00 ± 2.83^{Bb}	59.30 ± 6.65^{Bc}	62.96 ± 0.36^{Bd}
		300	4.76 ± 0.54^{Ba}	100,00 ± 0,00^{Bb}	65.75 ± 7.00^{Bc}	64.03 ± 0.18^{Bd}
	90	180	7.21 ± 0.39^{Ba}	100,00 ± 0,00^{Bb}	76.60 ± 5.09^{Bc}	63.72 ± 0.19^{Bd}

Grain	Temperature (°C)	Time (sec)	Moisture Content (%)	Mortality (%)	Temperature Difference (°C)	Color Difference (ΔE)
		240	5.73 ± 0.28^{Ba}	100,00 ± 0,00^{Bb}	79.30 ± 2.83^{Bc}	63.21 ± 0.10^{Bd}
		300	4.54 ± 0.54^{Ba}	100,00 ± 0,00^{Bb}	82.30 ± 0.71^{Bc}	64.47 ± 0.07^{Bd}
Chickpea	50	180	9.33 ± 0.01^{Ca}	6,00 ± 2.83^{Cb}	18.60 ± 1.70^{Cc}	61.55 ± 0.00^{Cd}
		240	7.61 ± 0.35^{Ca}	4,00 ± 0,00^{Cb}	21.20 ± 2.12^{Cc}	65.86 ± 8.49^{Cd}
		300	5.85 ± 0.02^{Ca}	6,00 ± 2.83^{Cb}	29.80 ± 0.99^{Cc}	59.13 ± 1.02^{Cd}
	70	180	8.62 ± 0.11^{Ca}	6,00 ± 2.83^{Cb}	38.50 ± 0.14^{Cc}	61.55 ± 0.07^{Cd}
		240	7.45 ± 0.16^{Ca}	98,00 ± 2.83^{Cb}	51.00 ± 1.56^{Cc}	61.72 ± 0.02^{Cd}
		300	5.58 ± 0.16^{Ca}	100,00 ± 0,00^{Cb}	56.05 ± 0.21^{Cc}	61.52 ± 0.06^{Cd}
	90	180	7.10 ± 0.11^{Ca}	52,00 ± 11.31^{Cb}	59.35 ± 1.20^{Cc}	60.96 ± 0.16^{Cd}
		240	6.18 ± 0.51^{Ca}	100,00 ± 0,00^{Cb}	67.85 ± 1.06^{Cc}	60.97 ± 0.40^{Cd}
		300	4.16 ± 0.01^{Ca}	100,00 ± 0,00^{Cb}	73.15 ± 0.21^{Cc}	61.56 ± 0.23^{Cd}
Lentil	50	180	8.79 ± 0.15^{Ba}	6,00 ± 2.83^{Bb}	22.75 ± 1.34^{Bc}	70.94 ± 0.04^{Bd}
		240	7.24 ± 0.13^{Ba}	0,00 ± 0,00^{Bb}	26.95 ± 0.49^{Bc}	71.86 ± 0.01^{Bd}
		300	6.09 ± 0.15^{Ba}	0,00 ± 0,00^{Bb}	31.30 ± 0.99^{Bc}	70.99 ± 0.04^{Bd}
	70	180	7.75 ± 0.01^{Ba}	8,00 ± 0,00^{Bb}	45.45 ± 1.06^{Bc}	70.76 ± 0.02^{Bd}
		240	6.73 ± 0.28^{Ba}	94,00 ± 2.83^{Bb}	57.75 ± 1.20^{Bc}	71.45 ± 0.06^{Bd}
		300	4.59 ± 0.29^{Ba}	100,00 ± 0,00^{Bb}	65.25 ± 0.92^{Bc}	70.70 ± 0.06^{Bd}

Grain	Temperature (°C)	Time (sec)	Moisture Content (%)	Mortality (%)	Temperature Difference (°C)	Color Difference (ΔE)
	90	180	7.02 ± 0.37^{Ba}	34,00 ± 2.83^{Bb}	70.55 ± 0.64^{Bc}	71.55 ± 0.08^{Bd}
		240	5.55 ± 0.28^{Ba}	100,00 ± 0,00^{Bb}	78.40 ± 0.14^{Bc}	70.41 ± 0.01^{Bd}
		300	3.94 ± 0.26^{Ba}	100,00 ± 0,00^{Bb}	82.00 ± 0.99^{Bc}	70.94 ± 0.08^{Bd}
Wheat	50	180	8.86 ± 0.03^{Da}	2,00 ± 2.83^{Db}	15.40 ± 2.40^{Dc}	69.33 ± 0.05^{Dd}
		240	8.44 ± 0.16^{Da}	8,00 ± 0,00^{Db}	26.30 ± 0.99^{Dc}	70.01 ± 0.01^{Dd}
		300	6.68 ± 0.01^{Da}	0,00 ± 0,00^{Db}	46.70 ± 22.34^{Dc}	70.83 ± 0.15^{Dd}
	70	180	8.46 ± 0.16^{Da}	0,00 ± 0,00^{Db}	42.75 ± 2.90^{Dc}	69.18 ± 0.34^{Dd}
		240	8.03 ± 0.13^{Da}	40,00 ± 5.66^{Db}	54.35 ± 0.21^{Dc}	70.50 ± 0.01^{Dd}
		300	3.95 ± 0.01^{Da}	100,00 ± 0,00^{Db}	60.40 ± 2.55^{Dc}	69.36 ± 0.06^{Dd}
	90	180	8.14 ± 0.88^{Da}	40,00 ± 5.66^{Db}	72.20 ± 1.56^{Dc}	70.68 ± 0.05^{Dd}
		240	5.61 ± 0.70^{Da}	100,00 ± 0,00^{Db}	76.60 ± 2.97^{Dc}	70.83 ± 0.07^{Dd}
		300	4.05 ± 0.44^{Da}	100,00 ± 0,00^{Db}	80.40 ± 1.98^{Dc}	69.52 ± 0.05^{Dd}

3.3 Effects of Ultrasound Exposure

The application of ultrasound at 100 kW exhibited distinct effects on red flour beetle mortality and grain quality parameters (Table 3, Table 6, Fig. 5). Mortality depended on exposure time, temperature and grain type. At 50°C, mortality was minimal across all grains, with 0% in buckwheat and chickpea after 1800 s, reflecting insufficient energy for insect inactivation. Increasing the temperature to 70°C significantly enhanced mortality; buckwheat and bulgur reached 100% after 1200–1800 s, while chickpea, lentil and wheat achieved full inactivation within the same time range. At 90°C, complete mortality was generally achieved more rapidly, for example, in buckwheat at 1200 s and lentil at 1200–1800 s. Moisture content trends were variable. In buckwheat, moisture increased slightly from 5.45% to 8.93% with longer exposure at 90°C, whereas chickpea remained relatively stable (6.48–8.69%), suggesting minor water redistribution rather than significant loss. Temperature differences

increased with both exposure time and temperature, ranging from 9.15°C (50°C/600 s) to 66.15°C (90°C/1800 s) in buckwheat, reflecting cumulative thermal effects from ultrasonic energy. Color difference (ΔE) remained relatively stable across all conditions (45–70), indicating minimal impact on visual quality. Pearson correlation analysis supported these observations: temperature strongly correlated with both temperature difference ($r = 0.760$, $p < 0.01$) and mortality ($r = 0.848$, $p < 0.01$), while exposure time positively correlated with temperature difference ($r = 0.582$, $p < 0.01$), mortality ($r = 0.254$, $p < 0.05$) and moisture content ($r = 0.379$, $p < 0.01$). Temperature difference was positively correlated with mortality ($r = 0.805$, $p < 0.01$) and weakly with moisture content ($r = 0.264$, $p < 0.05$), whereas mortality and moisture content were not significantly correlated ($p > 0.05$). Color difference showed no significant correlations ($p > 0.05$), suggesting minimal influence of US on visual properties (Table 3, Table 6, Fig. 5). Overall, ultrasound achieved complete inactivation of red flour beetle at higher temperatures (70–90°C) and extended exposure times (1200–1800 s), while maintaining moisture and color quality relatively well. Lower temperatures and shorter durations were insufficient for full control, highlighting the importance of optimizing US treatment parameters for each grain type. The response surfaces (Fig. 5) indicated that wheat and bulgur exhibited more pronounced responses, with greater changes in moisture and color at extended exposure, while buckwheat and lentil showed milder and more uniform surface effects. Chickpea showed nearly flat surfaces, suggesting limited energy transfer due to its denser and compact structure.

Table 3
Effects of ultrasound (US) exposure at 100 kW power on the red flour beetle in different grain types

Grain	Temperature (°C)	Time (sec)	Moisture Content (%)	Mortality (%)	Temperature Difference (°C)	Color Difference (ΔE)
Buckwheat	50	600	5,45 ± 0,16^{Aaa}	0,00 ± 0,00^{Aaa}	9,15 ± 2,76^{Aaa}	45,56 ± 0,32^{Aaa}
		1200	6,56 ± 0,30^{Aab}	0,00 ± 0,00^{Aab}	16,70 ± 3,11^{Aab}	46,21 ± 0,04^{Aab}
		1800	7,85 ± 0,18^{Aac}	0,00 ± 0,00^{Aac}	27,20 ± 3,11^{Aac}	46,38 ± 0,23^{Aac}
	70	600	6,81 ± 0,69^{Aba}	16,00 ± 0,00^{Aba}	27,90 ± 0,00^{Aba}	46,69 ± 0,08^{Aba}
		1200	7,72 ± 0,28^{Abb}	100,00 ± 0,00^{Abb}	36,50 ± 0,00^{Abb}	46,45 ± 0,01^{Abb}
		1800	6,66 ± 3,24^{Abc}	100,00 ± 0,00^{Abc}	48,40 ± 0,00^{Abc}	46,56 ± 0,03^{Abc}
	90	600	6,61 ± 0,15^{Aca}	94,00 ± 2,83^{Aca}	28,50 ± 2,69^{Aca}	45,58 ± 0,04^{Aca}
		1200	8,70 ± 0,56^{Acb}	100,00 ± 0,00^{Acb}	51,05 ± 2,90^{Acb}	46,04 ± 0,05^{Acb}
		1800	8,93 ± 1,40^{Acc}	100,00 ± 0,00^{Acc}	66,15 ± 4,74^{Acc}	45,82 ± 0,01^{Acc}
Bulgur	50	600	6,21 ± 2,09^{Caa}	0,00 ± 0,00^{Caa}	10,10 ± 3,25^{Caa}	63,43 ± 0,23^{Caa}
		1200	7,18 ± 0,09^{Cab}	0,00 ± 0,00^{Cab}	21,35 ± 2,05^{Cab}	63,58 ± 0,01^{Cab}
		1800	7,98 ± 0,37^{Cac}	2,00 ± 2,83^{Cac}	29,35 ± 3,04^{Cac}	64,16 ± 0,13^{Cac}
	70	600	6,06 ± 0,18^{Cba}	18,00 ± 2,83^{Cba}	29,95 ± 0,78^{Cba}	64,00 ± 0,01^{Cba}
		1200	7,95 ± 0,13^{Cbb}	100,00 ± 0,00^{Cbb}	39,90 ± 1,27^{Cbb}	62,96 ± 0,36^{Cbb}
		1800	7,92 ± 0,79^{Cbc}	100,00 ± 0,00^{Cbc}	53,75 ± 0,64^{Cbc}	64,03 ± 0,18^{Cbc}
	90	600	6,41 ± 0,38^{Cca}	96,00 ± 0,00^{Cca}	33,10 ± 1,70^{Cca}	63,72 ± 0,19^{Cca}
		1200	8,04 ± 0,70^{Ccb}	100,00 ± 0,00^{Ccb}	55,10 ± 2,26^{Ccb}	63,21 ± 0,10^{Ccb}

Grain	Temperature (°C)	Time (sec)	Moisture Content (%)	Mortality (%)	Temperature Difference (°C)	Color Difference (ΔE)
		1800	8,74 ± 0,55^{Ccc}	100,00 ± 0,00^{Ccc}	67,45 ± 4,74^{Ccc}	64,47 ± 0,07^{Ccc}
Chickpea	50	600	8,85 ± 0,15^{Baa}	0,00 ± 0,00^{Baa}	6,05 ± 2,76^{Baa}	61,55 ± 0,00^{Baa}
		1200	9,50 ± 1,03^{Bab}	0,00 ± 0,00^{Bab}	11,90 ± 2,55^{Bab}	65,86 ± 8,49^{Bab}
		1800	6,51 ± 0,84^{Bac}	0,00 ± 0,00^{Bac}	22,00 ± 2,69^{Bac}	59,13 ± 1,02^{Bac}
	70	600	6,80 ± 2,04^{Bba}	24,00 ± 5,66^{Bba}	25,00 ± 1,70^{Bba}	61,55 ± 0,07^{Bba}
		1200	8,31 ± 1,46^{Bbb}	100,00 ± 0,00^{Bbb}	31,65 ± 1,91^{Bbb}	61,72 ± 0,02^{Bbb}
		1800	8,69 ± 0,85^{Bbc}	100,00 ± 0,00^{Bbc}	45,40 ± 2,69^{Bbc}	61,52 ± 0,06^{Bbc}
	90	600	6,48 ± 1,05^{Bca}	100,00 ± 0,00^{Bca}	31,85 ± 3,04^{Bca}	60,96 ± 0,16^{Bca}
		1200	5,13 ± 1,44^{Bcb}	100,00 ± 0,00^{Bcb}	48,50 ± 2,40^{Bcb}	60,97 ± 0,40^{Bcb}
		1800	8,69 ± 0,85^{Bcc}	100,00 ± 0,00^{Bcc}	45,40 ± 2,69^{Bcc}	61,52 ± 0,06^{Bcc}
Lentil	50	600	4,77 ± 0,25^{Caa}	2,00 ± 2,83^{Caa}	6,95 ± 2,05^{Caa}	70,94 ± 0,04^{Caa}
		1200	6,91 ± 0,31^{Cab}	0,00 ± 0,00^{Cab}	12,90 ± 2,97^{Cab}	71,86 ± 0,01^{Cab}
		1800	8,13 ± 0,31^{Cac}	0,00 ± 0,00^{Cac}	23,35 ± 2,62^{Cac}	70,99 ± 0,04^{Cac}
	70	600	4,82 ± 0,13^{Cba}	14,00 ± 2,83^{Cba}	26,80 ± 2,12^{Cba}	70,76 ± 0,02^{Cba}
		1200	6,62 ± 0,09^{Cbb}	100,00 ± 0,00^{Cbb}	34,20 ± 2,55^{Cbb}	71,45 ± 0,06^{Cbb}
		1800	5,37 ± 3,65^{Cbc}	100,00 ± 0,00^{Cbc}	48,25 ± 3,61^{Cbc}	70,70 ± 0,06^{Cbc}
	90	600	5,41 ± 0,96^{Cca}	98,00 ± 2,83^{Cca}	35,00 ± 3,39^{Cca}	71,55 ± 0,08^{Cca}

Grain	Temperature (°C)	Time (sec)	Moisture Content (%)	Mortality (%)	Temperature Difference (°C)	Color Difference (ΔE)
		1200	6,63 ± 0,13C^{cb}	100,00 ± 0,00^{Ccb}	52,90 ± 3,96C^{cb}	70,41 ± 0,01^{Ccb}
		1800	8,57 ± 0,16^{Ccc}	100,00 ± 0,00^{Ccc}	68,40 ± 5,23^{Ccc}	70,94 ± 0,08^{Ccc}
Wheat	50	600	4,46 ± 0,13^{Caa}	0,00 ± 0,00^{Caa}	7,05 ± 2,33^{Caa}	69,33 ± 0,05^{Caa}
		1200	6,56 ± 0,89^{Cab}	0,00 ± 0,00^{Cab}	19,70 ± 3,11^{Cab}	70,01 ± 0,01^{Cab}
		1800	5,95 ± 0,21^{Cac}	4,00 ± 5,66^{Cac}	25,20 ± 2,69^{Cac}	70,83 ± 0,15^{Cac}
	70	600	6,38 ± 0,60^{Cba}	14,00 ± 2,83^{Cba}	23,55 ± 9,69^{Cba}	69,18 ± 0,34^{Cba}
		1200	6,59 ± 0,26^{Cbb}	100,00 ± 0,00^{Cbb}	39,20 ± 4,10^{Cbb}	70,50 ± 0,01^{Cbb}
		1800	7,14 ± 0,07^{Cbc}	100,00 ± 0,00^{Cbc}	51,95 ± 1,63^{Cbc}	69,36 ± 0,06^{Cbc}
	90	600	5,74 ± 0,30^{Cca}	90,00 ± 2,83^{Cca}	27,20 ± 2,55^{Cca}	70,68 ± 0,05^{Cca}
		1200	6,56 ± 0,28^{Ccb}	100,00 ± 0,00^{Ccb}	48,60 ± 3,82^{Ccb}	70,83 ± 0,07^{Ccb}
		1800	7,85 ± 0,38^{Ccc}	100,00 ± 0,00^{Ccc}	65,70 ± 2,69^{Ccc}	69,52 ± 0,05^{Ccc}

3.4 Comparative Analysis of Physical Treatments

Multivariate visualization of the effects of MW, IR and US treatments highlighted distinct patterns depending on treatment type, temperature, exposure time and grain characteristics (Fig. 2). MW treatment produced the most pronounced effects, particularly at higher temperatures (up to 90°C) and extended durations (up to 600 s), resulting in greater surface temperature differences and minor color variations. This is likely due to rapid volumetric heating and heterogeneous thermal gradients, which enhance localized insect inactivation. In contrast, infrared treatment showed a gradual and uniform effect across grains, indicating efficient surface heating with relatively stable moisture distribution. Ultrasound treatment caused moderate changes, primarily reflected in slight moisture and color differences, suggesting that cavitation and microstreaming generate subtler mechanical and thermal effects. Collectively, these observations indicate that treatment efficacy is determined not only by process variables but also by intrinsic grain structure and composition, aligning with previous reports in the literature (Fig. 2).

3.5 Implications for Grain Disinfestation

The data indicate that all three physical methods—MW, IR and US—can achieve full mortality of red flour beetle under appropriate conditions. MW treatment offers rapid inactivation but may induce localized heating and moisture loss, requiring careful parameter selection to balance insect control and quality preservation. Infrared treatment achieves uniform heating and gradual mortality increases, with minor impacts on color, suggesting it is suitable for grains sensitive to surface quality changes. Ultrasound offers a non-chemical alternative that preserves moisture and color, although complete mortality requires longer exposure at elevated temperatures. These results underscore the necessity of tailoring treatment parameters to grain type, structure and moisture content to maximize efficacy while minimizing quality degradation. The correlations between temperature, exposure time, temperature difference and insect mortality indicate that thermal accumulation is the primary mechanism of inactivation for both MW and IR treatments, whereas mechanical effects play a supplementary role in US treatments. Moisture reduction contributes to mortality under IR and MW, whereas under US, moisture changes are minimal. Color changes were generally minor across all treatments, suggesting that these methods can control red flour beetle without significantly affecting visual quality. Taken together, these findings support the use of MW, IR and US as effective, chemical-free methods for stored-product pest management, with potential applications in postharvest processing and storage systems. Optimal parameters must consider grain type, exposure time and treatment intensity to ensure complete insect inactivation while maintaining moisture and color quality. The results provide a comprehensive framework for developing tailored disinfestation protocols in the cereal and legume industry.

Table 4. Pearson correlation coefficients among different parameters for Microwave (MW) exposure at 100 kW power on the red flour beetle in different grain types

		Wavelength (nm)	Time (sec)	Temperature Difference (°C)	Mortality (%)	Moisture Content (%)	Color Difference (ΔE)
Wavelength (nm)	Pearson Correlation	1	0,000	,267**	,210*	-,382**	-0,004
	Sig. (2-tailed)		1,000	0,003	0,021	0,000	0,968
	N	120	120	120	120	120	120
Time (sec)	Pearson Correlation	0,000	1	,894**	,736**	-,664**	-0,002
	Sig. (2-tailed)	1,000		0,000	0,000	0,000	0,978
	N	120	120	120	120	120	120
Temperature Difference (°C)	Pearson Correlation	,267**	,894**	1	,640**	-,726**	0,011
	Sig. (2-tailed)	0,003	0,000		0,000	0,000	0,906
	N	120	120	120	120	120	120
Mortality (%)	Pearson Correlation	,210*	,736**	,640**	1	-,606**	0,006
	Sig. (2-tailed)	0,021	0,000	0,000		0,000	0,945
	N	120	120	120	120	120	120
Moisture Content (%)	Pearson Correlation	-,382**	-,664**	-,726**	-,606**	1	-0,019
	Sig. (2-tailed)	0,000	0,000	0,000	0,000		0,837
	N	120	120	120	120	120	120
Color Difference (ΔE)	Pearson Correlation	-0,004	-0,002	0,011	0,006	-0,019	1
	Sig. (2-tailed)	0,968	0,978	0,906	0,945	0,837	
	N	120	120	120	120	120	120

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 5. Pearson correlation coefficients among different parameters for Infrared (IR) exposure on the red flour beetle in different grain types

		Temperature (°C)	Time (sec)	Temperature Difference (°C)	Mortality (%)	Moisture Content (%)	Color Difference (ΔE)
Temperature (°C)	Pearson Correlation	1	0,000	,929**	,757**	-,498**	-0,011
	Sig. (2-tailed)		1,000	0,000	0,000	0,000	0,920
	N	90	90	90	90	90	90
Time (sec)	Pearson Correlation	0,000	1	,254*	,395**	-,789**	0,001
	Sig. (2-tailed)	1,000		0,016	0,000	0,000	0,989
	N	90	90	90	90	90	90
Temperature Difference (°C)	Pearson Correlation	,929**	,254*	1	,840**	-,679**	-0,011
	Sig. (2-tailed)	0,000	0,016		0,000	0,000	0,922
	N	90	90	90	90	90	90
Mortality (%)	Pearson Correlation	,757**	,395**	,840**	1	-,713**	-0,064
	Sig. (2-tailed)	0,000	0,000	0,000		0,000	0,551
	N	90	90	90	90	90	90
Moisture Content (%)	Pearson Correlation	-,498**	-,789**	-,679**	-,713**	1	-0,032
	Sig. (2-tailed)	0,000	0,000	0,000	0,000		0,765
	N	90	90	90	90	90	90
Color Difference (ΔE)	Pearson Correlation	-0,011	0,001	-0,011	-0,064	-0,032	1
	Sig. (2-tailed)	0,920	0,989	0,922	0,551	0,765	
	N	90	90	90	90	90	90

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 6. Pearson correlation coefficients among different parameters for ultrasound (US) exposure at 100 kW power on the red flour beetle in different grain types

		Temperature (°C)	Time (sec)	Temperature Difference (°C)	Mortality (%)	Moisture Content (%)	Color Difference (ΔE)
Temperature (°C)	Pearson Correlation	1	0,000	,760**	,848**	0,039	-0,011
	Sig. (2-tailed)		1,000	0,000	0,000	0,717	0,920
	N	90	90	90	90	90	90
Time (sec)	Pearson Correlation	0,000	1	,582**	,254*	,379**	0,002
	Sig. (2-tailed)	1,000		0,000	0,016	0,000	0,989
	N	90	90	90	90	90	90
Temperature Difference (°C)	Pearson Correlation	,760**	,582**	1	,805**	,264*	-0,008
	Sig. (2-tailed)	0,000	0,000		0,000	0,012	0,941
	N	90	90	90	90	90	90
Mortality (%)	Pearson Correlation	,848**	,254*	,805**	1	0,138	-0,008
	Sig. (2-tailed)	0,000	0,016	0,000		0,194	0,942
	N	90	90	90	90	90	90
Moisture Content (%)	Pearson Correlation	0,039	,379**	,264*	0,138	1	-0,185
	Sig. (2-tailed)	0,717	0,000	0,012	0,194		0,081
	N	90	90	90	90	90	90
Color Difference (ΔE)	Pearson Correlation	-0,011	0,002	-0,008	-0,008	-0,185	1
	Sig. (2-tailed)	0,920	0,989	0,941	0,942	0,081	
	N	90	90	90	90	90	90

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

4. Discussion

The present study evaluated the effectiveness of MW, IR and US treatments as non-chemical disinfestation methods for controlling the red flour beetle in various stored grains. The results demonstrated that all three

methods were capable of achieving complete adult mortality under specific combinations of temperature and exposure time, while maintaining acceptable grain quality. These findings are in line with recent research highlighting the potential of physical methods as sustainable alternatives to chemical fumigation (Gaurav Kumar and Rai, 2013; Vadivambal et al., 2008).

4.1 Microwave treatment

Microwave heating induced significant effects on insect mortality, temperature rise and moisture reduction across all grain types. Increasing power and exposure time enhanced insect lethality, consistent with earlier studies showing that higher microwave energy accelerates mortality through rapid volumetric heating (Halverson et al., 1996; Tayeb et al., 2018). For instance, Tayeb et al. (2018) reported 100% mortality of the red flour beetle at 800 W for 20 s, a result comparable to the present findings. Moisture reduction during MW exposure reflects the combined effects of water evaporation and internal heating, both of which contribute to insect inactivation (Abdullahi and Dandago, 2021). The observed weak correlation between color difference and treatment parameters suggests that MW heating, although intense, did not severely compromise the visual quality of the grains. Nevertheless, literature emphasizes that non-uniform heating can occur due to differences in dielectric properties, particle size and density (Vadivambal et al., 2008), indicating the need for optimization to prevent localized overheating and maintain nutritional quality.

4.2 Infrared treatment

Infrared exposure produced a temperature-dependent increase in insect mortality, with full disinfestation achieved at 70–90°C and prolonged exposure times. These findings corroborate those of Keszthelyi et al. (2021), who reported that increasing IR temperature led to a rapid decline in *Sitophilus granarius* survival rates. The consistent decrease in grain moisture observed in this study is also aligned with previous reports linking dehydration with insect mortality under IR heating (Abdullahi and Dandago, 2021). Furthermore, color difference values remained largely stable across temperature ranges, indicating that IR radiation induced only minor visual changes. Similar trends were documented by Ibrahim et al. (2019), who observed that IR treatment effectively inactivated storage insects while preserving the external appearance of treated grains. These results suggest that IR technology may be particularly suitable for grains where maintaining surface color and appearance is critical.

4.3 Ultrasound treatment

Ultrasound (US) exposure demonstrated that mechanical and cavitation effects can supplement mild thermal processes to achieve complete pest inactivation at higher temperatures (70–90°C) and longer durations. The strong positive correlation between temperature difference and mortality observed here aligns with previous studies indicating that the combined mechanical and thermal effects of ultrasound contribute to insect mortality (Rudik et al., 2020). However, at lower temperatures, mortality rates remained minimal, suggesting that US alone may be insufficient for rapid control. The relatively stable moisture content and color difference values observed across all conditions indicate that US treatment is less destructive to grain quality than MW or IR methods. This outcome supports the notion that US technology may serve as a quality-preserving approach within integrated pest management systems, though optimization of exposure parameters remains necessary for industrial feasibility (Abdullahi and Dandago, 2021).

4.4 Comparative assessment and implications

Comparative analysis across MW, IR and US treatments revealed distinct performance patterns. MW achieved the fastest and most complete insect inactivation, attributed to volumetric and heterogeneous heating. IR treatment resulted in more uniform heating and gradual mortality increases, while US caused moderate mechanical and thermal effects that preserved grain quality. These observations align with previous comparative evaluations of physical disinfestation techniques (Vadivambal et al., 2008; Gaurav Kumar and Rai, 2013). Overall, the results suggest that thermal accumulation is the dominant mechanism of inactivation for MW and IR treatments, whereas mechanical forces play a supplementary role under US conditions. Moisture reduction further enhances lethality in MW and IR processes, while remaining negligible under US treatment. Minor color variations across all treatments confirm that these non-chemical methods can effectively control stored-product pests without compromising visual quality. From an applied perspective, the optimization of treatment parameters according to grain type, structure and composition is critical. Bulgur and wheat exhibited higher temperature gradients and faster insect mortality, while lentil and chickpea, due to their denser matrices and lower thermal conductivity, required longer exposure. These findings contribute to the development of tailored, eco-friendly disinfestation protocols suitable for the cereal and legume industry.

5. Conclusions

This study comprehensively examined the effectiveness of MW, IR and US treatments as environmentally sustainable, non-chemical strategies for the control of the red flour beetle in stored grains. Across all tested grain types—wheat, bulgur, buckwheat, lentil and chickpea—each treatment demonstrated strong potential to achieve complete insect inactivation under appropriate thermal or acoustic conditions, without causing significant deterioration in grain quality.

MW treatment achieved the most rapid and complete mortality, primarily due to volumetric dielectric heating that allowed for uniform internal energy transfer. Mortality rates reached 85–100% within short exposure durations (10–40 s) as power increased from 360 to 900 W. However, higher energy levels were also associated with slight moisture loss and moderate temperature gradients, indicating the need for precise control of exposure time to avoid over-drying. IR exposure produced uniform surface heating and gradual increases in mortality, reaching up to 98–100% at 70–90°C and 240–300 s. The relatively small color difference values ($\Delta E < 2.5$) indicated that IR treatment maintained visual grain quality while effectively reducing moisture and achieving high insect mortality. The slower but more homogeneous heating profile of IR suggests its suitability for grain types where visual and textural integrity are critical, such as bulgur and chickpea. US treatment relied on a combination of mechanical vibration, cavitation and mild thermal effects to induce mortality. Although complete inactivation required longer exposure (1200–1800 s) and higher temperatures (70–90°C), US preserved grain moisture and color better than the other two methods. Its gentle processing conditions make it a promising option for quality-sensitive grains, complementing MW and IR treatments within integrated pest management systems.

Correlation analyses confirmed that temperature and exposure time were the dominant parameters influencing red flour beetle mortality, while moisture content exhibited a negative relationship with mortality in MW and IR treatments. Color difference (ΔE) showed no significant correlation with process parameters, supporting the conclusion that physical disinfestation can be achieved without substantial visual degradation. Grain-specific differences also played a decisive role: smaller, low-density grains such as buckwheat and lentil absorbed energy more efficiently, leading to faster mortality, whereas denser grains like wheat and chickpea required

longer exposure to reach lethal thresholds. Overall, the combined results demonstrate that MW, IR and US are promising, residue-free, and sustainable disinfestation technologies capable of providing effective control of the red flour beetle in a range of stored grains. Each method presents distinct advantages—rapid treatment for MW, uniform heating for IR, and quality preservation for US—highlighting their complementary potential in postharvest pest management. Future studies should expand on multi-stage insect development, pilot-scale validation and the long-term impact of these treatments on grain storage stability, nutritional composition and sensory attributes. Integrating these green physical technologies into industrial grain handling systems offers a viable pathway toward safer, more sustainable and pesticide-free food preservation.

This study provides a comprehensive comparative assessment of three physical disinfestation technologies across multiple grain types, elucidating the complex relationships among temperature, exposure time, moisture and insect mortality. Although the experimental design effectively demonstrated method efficiency, limitations include the laboratory scale of treatment and focus on adult insects only. Future research should therefore explore multi-stage pest development (egg, larva, pupa), large-scale trials and long-term impacts on grain germination, nutritional value and storage stability. Expanding the integration of physical methods into postharvest pest management strategies could substantially reduce chemical pesticide dependence and enhance food safety and sustainability.

Declarations

Declaration of Competing Interest

The researchers acquaint that they have no competing financial or individual connections that may influence the work reported in this manuscript.

Author Contribution

A.Y.: Conceptualization, Methodology, Formal analysis, Acquisition of data, Visualization, Writing-original draft, Writing-review and editing. M.B.: Investigation, Conceptualization, Project administration, Supervision, Writing-review and editing.

Acknowledgement

The researchers are grateful to the Scientific Research Projects Coordination Unit of Gaziantep University for the financial support of the project numbered MFDT.2417

References

1. Abdullahi, N., Dandago, M. A. (2021). Postharvest losses in food grains–A Review. *Turkish Journal of Food and Agriculture Sciences*, *3*(2), 25–36.
2. Anumudu, C. K., Onyeaka, H., Ekwueme, C. T., Hart, A., Isaac-Bamgboye, F., Miri, T. (2024). Advances in the application of infrared in food processing for improved food quality and microbial inactivation. *Foods*,

13(24), 4001.

3. Athanassiou, C. G., Arthur, F. H., Campbell, J. F. (2019). Biology and management of *Tribolium castaneum* (Coleoptera: Tenebrionidae). *Journal of Stored Products Research*, *82*, 1–14. https://doi.org/10.1016/j.jspr.2019.02.001
4. Bassey, F. I., Chinnan, M. S., Ebenso, E. E., Edem, C. A., Iwegbue, C. M. A. (2013). Colour Change: An Indicator of the Extent of Maillard Browning Reaction in Food System. *Asian Journal of Chemistry*, *25*(16).
5. Boxall, R. A. (2002). Damage and loss caused by the larger grain borer *Prostephanus truncatus*. *Integrated Pest Management Reviews*, *7*(2), 105–121. https://doi.org/10.1023/A:1026397115946
6. Fakude, M. P. (2009). *Eradication of storage insect pests in maize using microwave energy and the effects of the latter on grain quality*. University of Pretoria (South Africa).
7. Fields, P. G., White, N. D. G. (2002). Alternatives to methyl bromide treatments for stored-product and quarantine insects. *Annual Review of Entomology*, *47*(1), 331–359. https://doi.org/10.1146/annurev.ento.47.091201.145217
8. Gaurav Kumar, G. K., Rai, D. V. (2013). Management strategies for storage, disinfestation and insect detection of grains and seeds.
9. 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.
10. Hardy, J., Parmentier, M., Fanni, J. (1999). Functionality of nutrients and thermal treatments of food. *Proceedings of the Nutrition Society*, *58*(3), 579–585.
11. Hashem, A. S., Abdelwahab, A. H., Shahat, M. A., Alharbi, J., Alhamadi, K. J., Khalil, F., Al-Rashidi, H.S., Alghamdi, T., Mahyoub J. A., Aljameeli, M. M. (2025). Synergistic Use of Phosphine and Botanical Fumigants: A Sustainable Strategy for Pest Resistance Mitigation and Postharvest Food Protection. *Journal of Crop Health*, *77*(5), 166.
12. Herrick, N. J., Mankin, R. W. (2012). Acoustical detection of *Sitophilus zeamais* (Coleoptera: Curculionidae) and *Tribolium castaneum* (Coleoptera: Tenebrionidae) in stored grain. *Journal of Economic Entomology*, *105*(6), 2023–2030. https://doi.org/10.1603/EC12195
13. Hodges, R. J., Buzby, J. C., Bennett, B. (2014). Postharvest losses and waste in developed and less developed countries: Opportunities to improve resource use. *Journal of Agricultural Science*, *152*(S1), 37–45. https://doi.org/10.1017/S0021859613000836
14. Ibrahim, A. I., Yousry, M. A., Saad, M. I., Mahmoud, M. F., Said, M., Ameen, A. (2020). Infrared thermal imaging as an innovative approach for early detection infestation of stored product insects in certain stored grains. *Cercetari Agronomice in Moldova (Agronomic Research In Moldavia)* LII, *4* (180), 321–331 DOI:10.2478/cerce-2019-0031
15. Ikediala, J. N., Hansen, J. D., Tang, J., Drake, S. R. (1999). Development of a saline water immersion technique with microwave heating for postharvest control of codling moth in cherries. *Postharvest Biology and Technology*, *16*(2), 127–139. https://doi.org/10.1016/S0925-5214(99)00018-2
16. Kumar, R., Kumar, A., nd Singh, K. (2019). Effect of microwave treatment on physico-chemical and nutritional properties of cereal grains. *Journal of Food Science and Technology*, *56*(3), 1525–1534. https://doi.org/10.1007/s13197-019-03622-0

17. Keszthelyi, S., Lukács, H., Pál-Fám, F. (2021). Effects of different infra-red irradiations on the survival of granary weevil Sitophilus granarius: bioefficacy and sustainability. *Insects*, *12*(2), 102.
18. Mahroof, R., Subramanyam, B., Maier, D. (2003). 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. https://doi.org/10.1016/S0022-474X(02)00071-8
19. Mariadoss, A., Sujeetha, A. R., Sankarganesh, E. (2025). Challenges and Issues Associated with Chemical Methods of Fumigation. *Non-chemical Methods for Disinfestation of Stored Products*, 60–74.
20. Mankin, R. W., Hagstrum, D. W., Smith, M. T., Roda, A. L., Kairo, M. T. K. (2011). Perspective and promise: A century of insect acoustic detection and monitoring. *American Entomologist*, *57*(1), 30–44. https://doi.org/10.1093/ae/57.1.30
21. Mydeen, V. J. P., Sachithanandhan, V. K., Vijayaram, E. N., Manickam, L., Shanmugasundaram, S., Veerapandian, C. (2025). Mechanical Approaches for Insect Management in Grain Storage: Detection, Prevention and Control. In *Non-chemical Methods for Disinfestation of Stored Products* (pp. 256–287). CRC Press.
22. Nelson, S. O. (1996). Review and assessment of radio-frequency and microwave energy for stored-grain insect control. *Transactions of the ASAE*, *39*(4), 1475–1484. https://doi.org/10.13031/2013.27657
23. Ouaarous, M., El Fakhouri, K., Taarji, N., Baouchi, A., Amri, M., Ramdani, C., Sobeh, M., Mesfioui, A., El Bouhssini, M. (2025). Impact of Field Insect Pests on Seed and Nutritional Quality of Some Important Crops: A Comprehensive Review. *ACS omega*, *10*(9), 8779–8792.
24. Phillips, T. W., Throne, J. E. (2010). Biorational approaches to managing stored-product insects. *Annual Review of Entomology*, *55*(1), 375–397. https://doi.org/10.1146/annurev.ento.54.110807.090451
25. Rudik, F. Y., Morgunova, N. L., Krasnikova, E. S. (2020). Decontamination of grain by ultrasound. In *IOP Conference Series: Earth and Environmental Science, 421*(2), p. 022022. IOP Publishing.
26. Sabri, S. (2025). The Effect of Microwave Electromagnetic Radiation on Microorganisms and Stored Grain Pests in Iraqi Local Wheat. *Journal of Agriculture, Food, Environment and Animal Sciences*, *6*(1), 113–122.
27. Sadekla, S., Menapace, L., Ola, O. (2025). Sustainable postharvest processing technologies for dried food commodities and firm-level adoption: A critical review. *Journal of Stored Products Research*.
28. Srivastava, S., Mishra, H. N. (2021). Ecofriendly nonchemical/nonthermal methods for disinfestation and control of pest/fungal infestation during storage of major important cereal grains: A review. *Food Frontiers*, *2*(1), 93–105.
29. Subramanyam, B., Mahroof, R. (2014). Heat treatment of food processing facilities for insect management. In D. W. Hagstrum, T. W. Phillips, G. Cuperus (Eds.), *Stored product protection* (179–189). Kansas State University.
30. Tayeb, E., Saad, A., Abdelmageed, A. A., Al-Besaerawi, M. (2018). Microwave radiation as an eco-friendly tool for controlling the red flour beetle tribolium castaneum (hbst.)(Coleoptera: Tenebrionidae). *Journal of the Advances in Agricultural Researches*, *23*(4), 584–599.
31. Vadivambal, R., Jayas, D. S., White, N. D. (2008). Mortality of stored-grain insects exposed to microwave energy. *Transactions of the ASABE*, *51*(2), 641–647.
32. Vadivambal, R., Jayas, D. S. (2010). Non-uniform temperature distribution during microwave heating of food materials—A review. *Food and Bioprocess Technology*, *3*(2), 161–171. https://doi.org/10.1007/s11947-008-

Figures

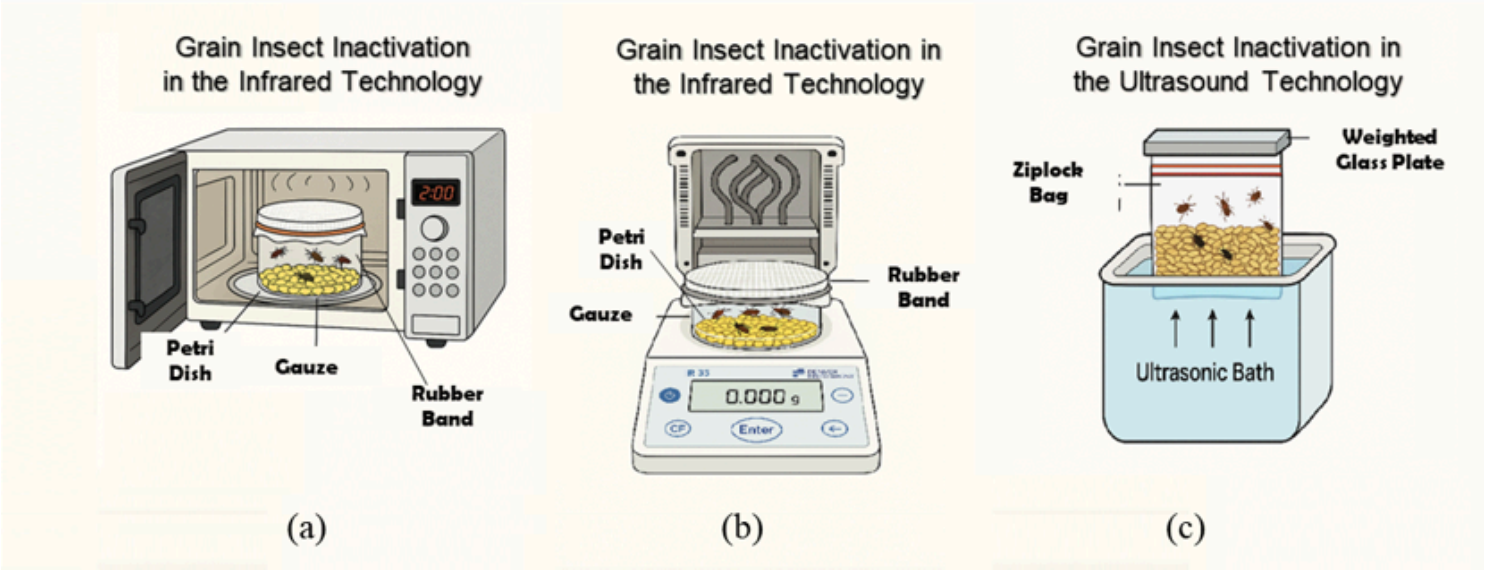


Figure 1

Schematic illustration of the experimental setups employed for the red flour beetle inactivation using (a) microwave, (b) infrared and (c) ultrasound technologies.

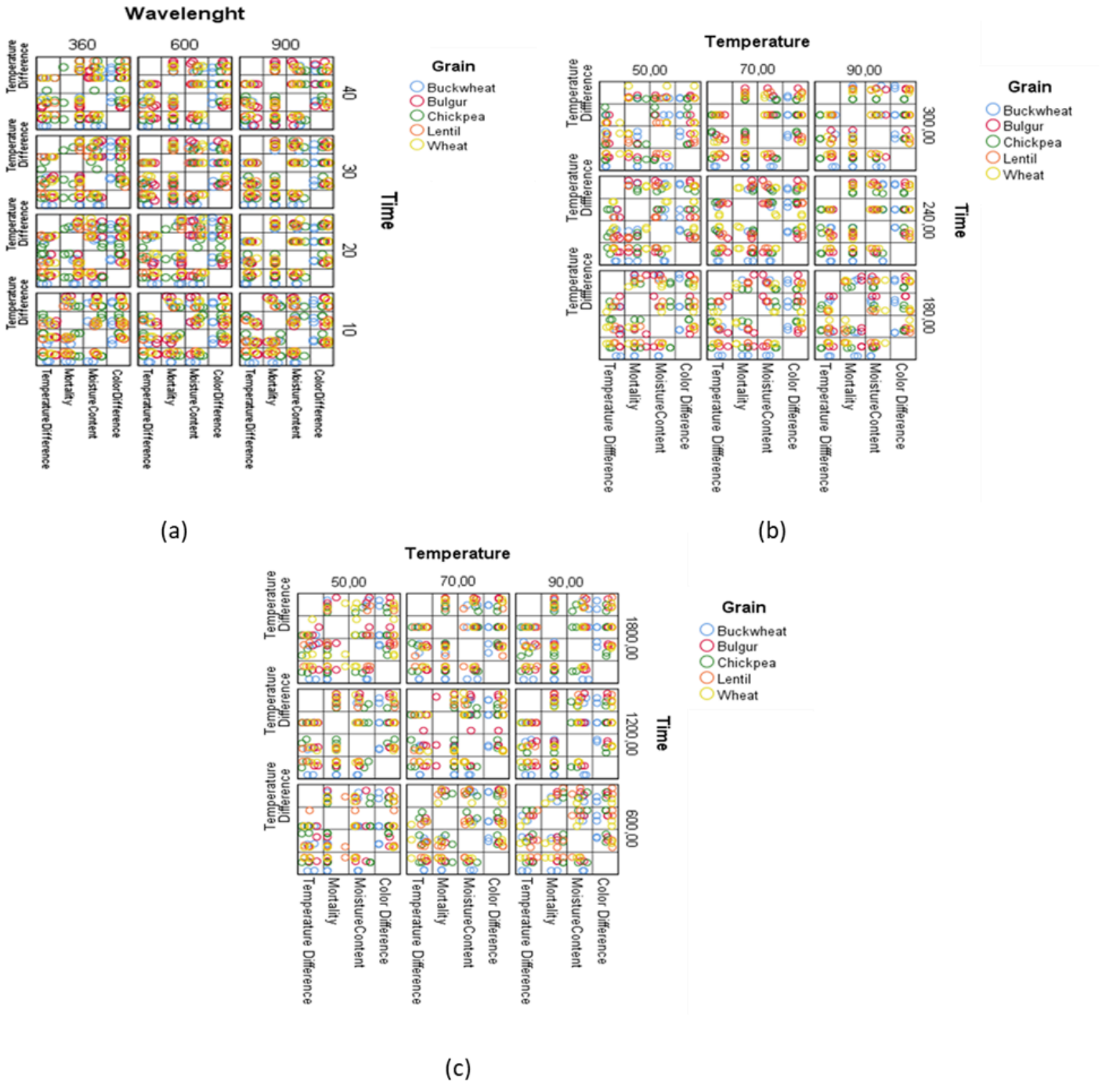


Figure 2

Multivariate visualization of the effects of physical treatments using (a) microwave, (b) infrared and (c) ultrasound technologies. on the red flour beetle responses in different grain matrices

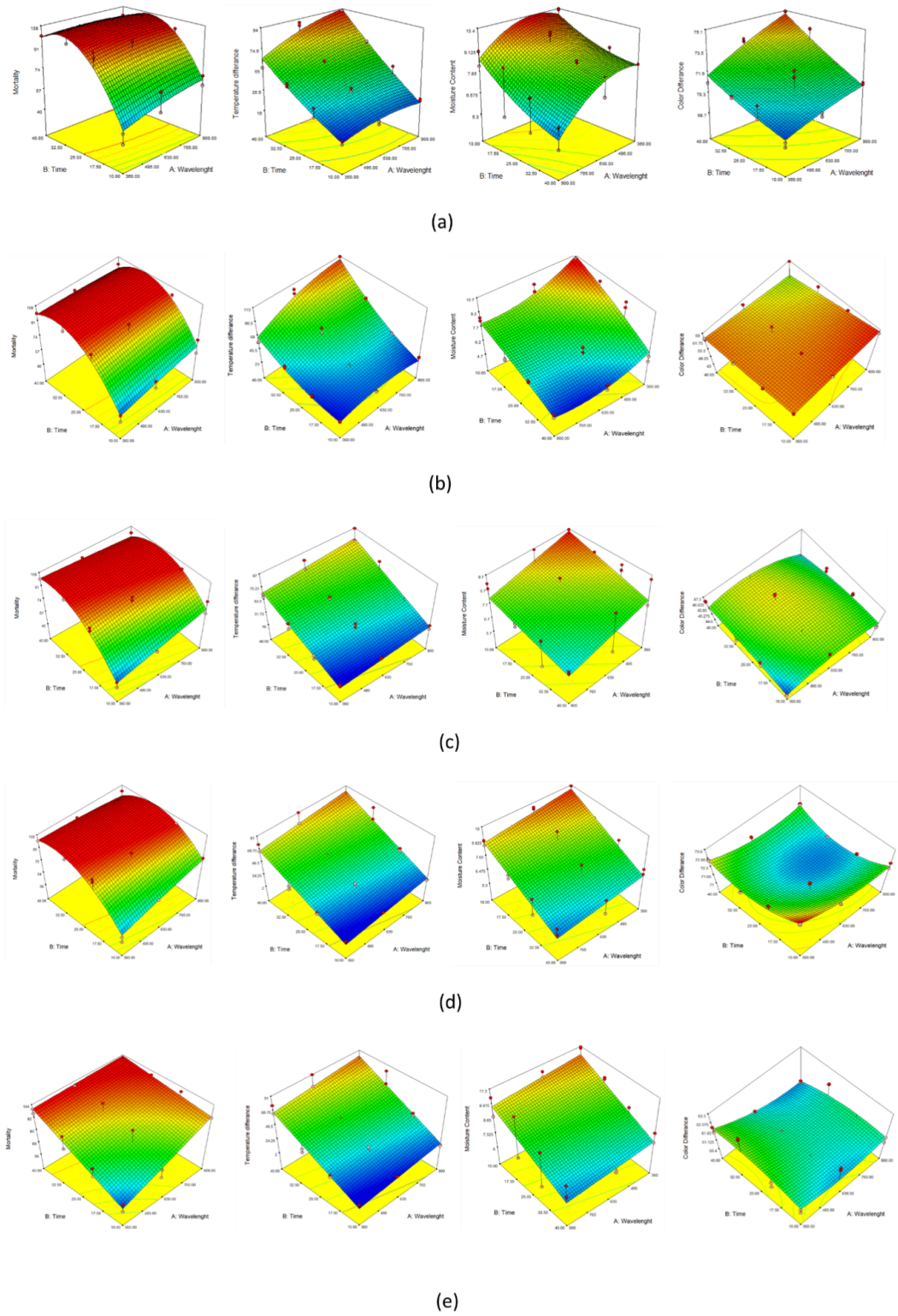


Figure 3

Response surface plots showing the effect of microwave inactivation parameters (time and wavelength) of the red flour beetle on measured properties of different grains and legumes: (a) wheat, (b) bulgur, (c) buckwheat, (d) lentil and (e) chickpea.

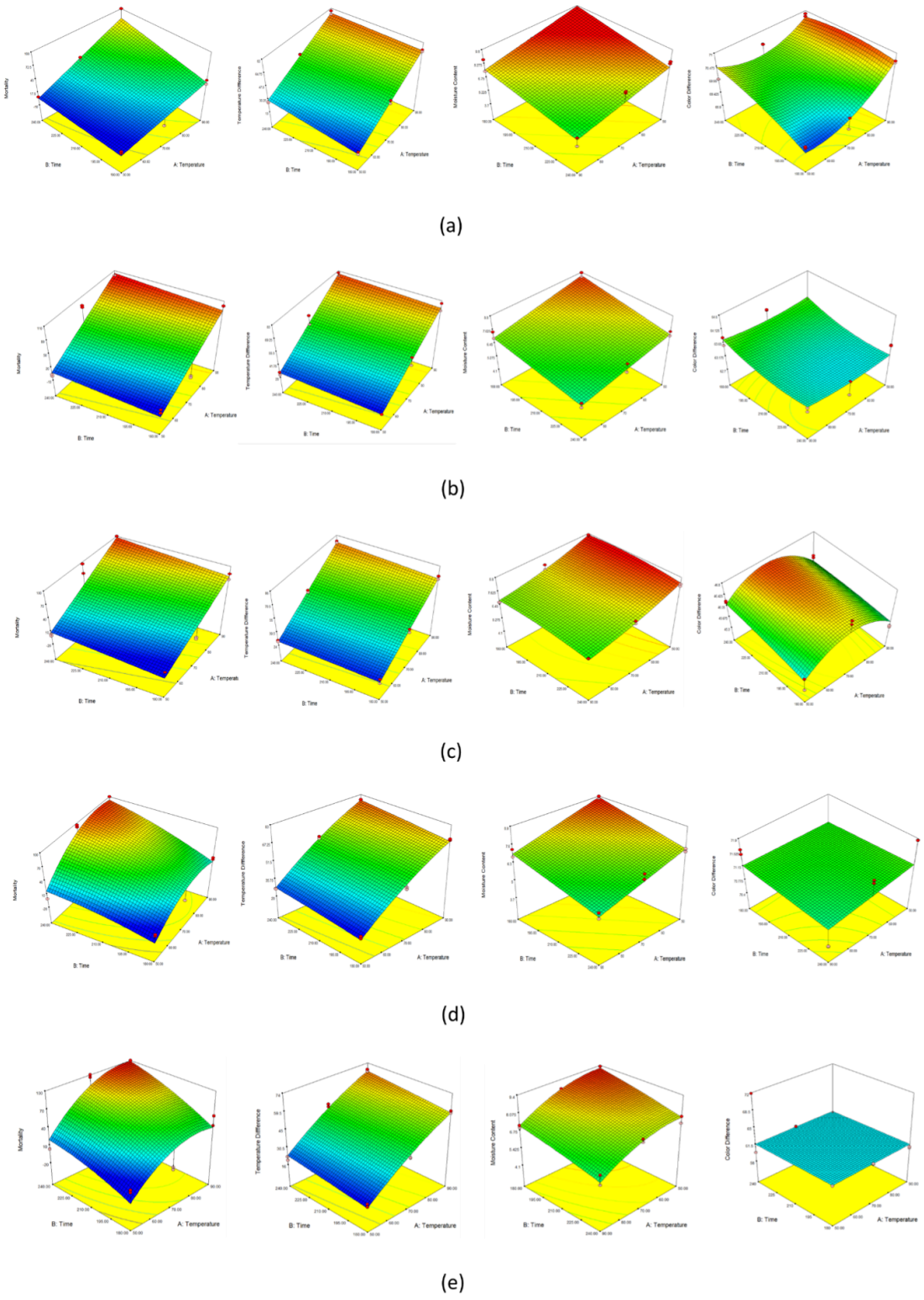


Figure 4

Response surface plots showing the effect of infrared inactivation parameters (time and wavelength) of the red flour beetle on measured properties of different grains and legumes: (a) wheat, (b) bulgur, (c) buckwheat, (d) lentil and (e) chickpea.

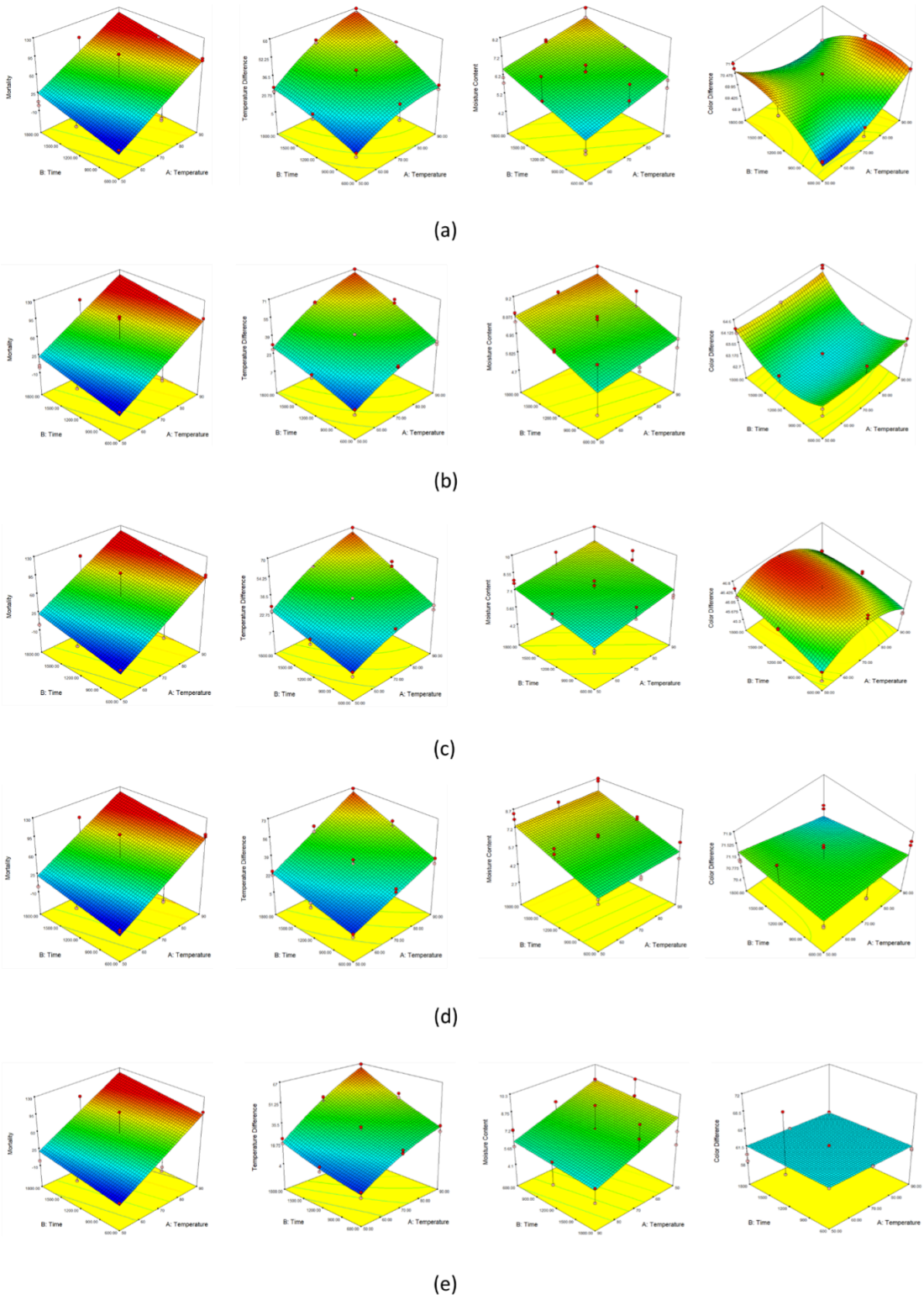


Figure 5

Response surface plots showing the effect of ultrasound inactivation parameters (time and wavelength) of the red flour beetle at 100 kW on measured properties of different grains and legumes: (a) wheat, (b) bulgur, (c) buckwheat, (d) lentil and (e) chickpea.