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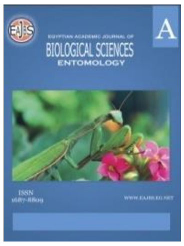

Thermal Disinfestation of Stored Grain Insects Using Solar Energy

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ABSTRACT

Chemical control, especially fumigants, is the most used method to control stored-grain pests. A safer alternative for disinfestation is to heat grains to a temperature of 50-60ºC. However, this alternative consumes high thermal energy due to the relatively high temperature required to achieve the required goal. In the present paper, a grain solar heating system has been developed to achieve this high temperature/short time technique to control *Callosobruchus maculatus*, one of the most common pests of many legumes. The solar heating system provides an attractive alternative to conventional electric heating systems or gas-fired heating systems. The present results show that the proposed system is successful in suppressing *C. maculatus* population within 115 min under temperatures from 55 to 57ºC. This thermal range is capable of controlling most of the stored grain insects. Employing solar heating provides a simple, energy-saving alternative to small and medium-scale applications.

INTRODUCTION

Grain and legume production is crucial to achieving global food security for humankind. The global population was 7.8 billion in 2020 and is expected to reach ≈ 9.8 to 10.5 billion by 2050. Subsequently, this implies an increase in global food demands by 50 to 70% (Affognon *et al.,* 2015; Aulakh *et al.,* 2013; Mesterházy *et al.*, 2020). The grain losses during harvest and storage are about 83% of the annual stored grains (Mesterházy *et al.,* 2020). Postharvest damage is mainly caused by insect pests and mold. It has been reported that grain losses are ≈ 1-2% in developed countries, while it could reach up to 20-50% in developing countries where they used traditional storage systems (Mesterházy *et al.*, 2020). In some cases, insects are responsible for a total loss of ≈ 57 and 92% in maize in Kenya and Zimbabwe, respectively (Sallam, 2000). Globally, insect pests are responsible for considerable post-harvest grain loss (Fürstenau and Kroos, 2020; Nayak

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and Daglish, 2018). Therefore, postharvest pest control is very important, and the sustainability of the production of high-quality grains and legumes is a huge task and essential for human food and animal production. Achieving food security and food demands is also important to achieve sustainable development goals (SDGs) for the 2030 world agenda adopted by united nations members (FAO *et al.,* 2020).

Legumes are one of the main constituents of the human diet and livestock diet, especially in developing countries in Africa and Asia. Recent years have seen a rising interest in legumes and their benefits as a healthy diet worldwide. Pulse grains are known as dietary rich in protein, carbohydrates, fibers, and minerals (Bouchenak and Lamri-Senhadji, 2013; De Cillis *et al.,* 2019). Therefore, pulses are considered an alternative high-protein diet to dietary meat, especially in areas where most people are suffering from poverty and low-quality diet. Legumes crops also help in the enhancement of soil properties and agricultural sustainability (L'Hocine *et al.,* 2020). Faba beans are the main pulse grains used in the Egyptian diet (Barakat, 2020). Therefore, the reduction of postharvest loss is crucial in the food chain system.

Legumes are attacked by several insect groups. One of the most destructive insect groups is bruchids. Some bruchids cause a substantial economic loss to stored legume seeds ranging from 51% to about 68% within three months of storage (Aly *et al.,* 2005). *Callosobruchus maculatus* (Coleoptera: Chrysomelidae: Bruchinae) is one of the most destructive pests for broad beans and other pulses in Egypt.

Thermal control for stored grain insects has been used since ancient times. Traditional methods have used heat, particularly solar energy, for thousands of years (Ajayi *et al.,* 2021; Fields, 1992; Lale and Vidal, 2003; Murdock and Shade, 1991). Thermal disinfestation of stored-grain pests has grown as an effective, environmentally friendly alternative to traditional chemical control methods. Several techniques have evolved for heat disinfestation. Some of these techniques have been used to disinfest bulks of stored grains (Mourier and Poulsen, 2000), while others have been targeting heat disinfestation of large silos and warehouses (Beckett *et al.,* 2007). Thermal disinfestation of stored-grain insects has been used successfully in many developed and developing countries (Beckett *et al.,* 2007). This area of research has been investigated from different aspects, and much information is available concerning the lethal heat limits for different insect species, grain quality, and heating principles in both lab and industrial-scale trials (Beckett *et al.,* 2007).

Solar disinfestation is a promising technique for the thermal control of stored grain insects. Several studies have been investigating the use of solar energy directly or indirectly for thermal control of stored products and commodities. Direct solar radiation is mainly used on small-scale trials, while indirect solar energy is used for medium to large-scale trials. For heat disinfestation, Muhammad *et al.* (2006) used direct solar radiation and galvanized steel bins (with 2400 to 3000 kg of wheat). On the other hand, Thorpe (1998) used indirect solar energy for cooling control of stored wheat pests in a tube-like metal cylinder.

The current work is directed to small-medium scale levels targeting small farm holders and small industries by using alternative safe and applicable methods for stored-grain pest control rather than chemical control. This is achieved by the designing of a heat disinfestation system of grains using solar energy as a renewable source of energy instead of electric energy, especially in a country like Egypt with sunny days almost throughout the whole year. In the proposed system, solar energy is used to heat up water as a working fluid. Hot water is circulated in pipe coils inside the grain heater and returned back to a buffer tank. Water in the buffer tank is directly heated by solar heat through evacuated tube solar receivers. An auxiliary water heater is used in the buffer tank when solar energy is not available. This guarantees sufficient solar energy that is supplied for the solar heater during the summer and winter seasons.

The main objective is to develop an efficient solar heating system to increase grain temperature over a relatively limited period of time. The system is designed to achieve lethal temperatures for stored-grain insects, 50 -60°C. The system's effectiveness will be measured by reaching the best temperature and time combination for each insect species without affecting the quality of the seeds.

MATERIALS AND METHODS

1-Design of Solar Disinfestation System:

The core point of this project is the designing and construction of the solar seed disinfestation system. This system depends on solar energy as a renewable source of energy. The following sections illustrate the system's components.

1.1. Solar Collector (Active System)

Westech (Westech, 2022) Split Pressurized Solar Water Heater Model SP-WT-58 (300 L) was installed (Fig. 1). The heating system relies on electric pumps to circulate fluid through the solar collectors. In this system, the water in a storage tank is directly filled using the hot water flowing from the solar collectors (single loop).

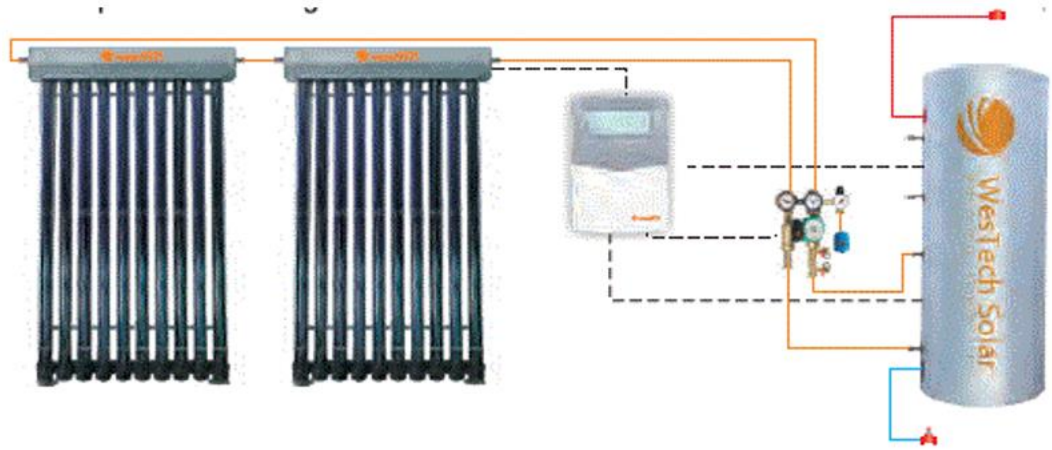

Fig. 1. Schematic diagram of the solar heating system (Westech Manual).

1.2. Grain Hopper Design:

The grain hopper is a galvanized steel tank that contains grains or seeds to be disinfested by heating. The temperature of grains can be controlled by the mount of grains contained inside the hopper and the amount of energy transported to the grains trapped inside the hopper. The grain hopper is a double-walled cylindrical tank made of galvanized steel (Fig.2). The inner radius is 0.145 m and the outer radius is 0.390 m. The height of the container is 0.45 m. The hopper volume is approximately 38 Litres and the heating surface area is 0.7 m^2. Hot water coils pass through the double walls of the outer tank wall. A double-walled core cylinder was provided in which a hot water coil passes through the core. The hot-water coils are helical in shape to maximize the heat transfer area. Two helix-shaped copper pipes were added to the hopper to maximize its heating capacity. Polyurethane foam was sprayed around the two helix-shaped copper pipes as a thermal insulator. The grain hopper had an insulated metal cover and an insulated bottom gate to discharge the grains.

A fork-shaped connector with two ends of stainless-steel flexible hose pipes with water valves was used to connect the water storage tank of the solar heater to the grain hopper. One end of the fork-shaped connector was connected to the inner coil of the grain hopper, while the other end was connected to the outer coil of the hopper. Before the fork diversion, an additional water valve was added to adjust the water flow rate entering the grain hopper.

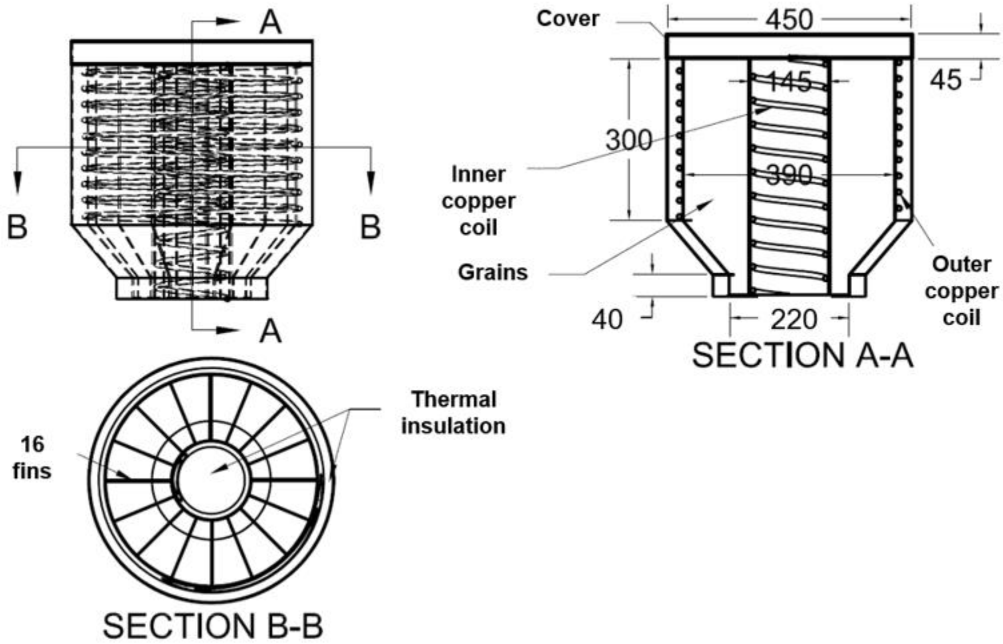

Fig. 2. Geometry of the grain hopper used in the experiments.

2-Mathematical Model Development:

To optimize the use of the grain solar heater, a mathematical model was developed to calculate the time required to operate the heater to achieve the desired temperature for optimum grain disinfestation. Different parameters have been included: the mass capacity of the hopper (M_g) per run and the specific heat of the common Faba beans (Cg). The mass capacity of the grain hopper was calculated assuming a bulk density of 874 kg/m^3 (Matouk et al., 2018). The specific heat of Faba beans typically ranges from 3.1 to 3.5 kJ/kg at 40^{o}C and ranges from 2.7 to 3.1 at 60^{o}C, (Matouk et al., 2018). In the present work, Cg is assumed to be constant and equal to 3.2 kJ/kg^{o}C. The hot water mass flow rate was adjusted to 21 mL/s. These parameters also include the initial and final temperature of the grains, T_i and T_f, respectively, and the inlet and outlet hot water temperatures, T_{wi} and T_{wo}, respectively. Another important variable for heat transfer through beans is the porosity of the grain (ε), which is defined as the fraction of the grain (bean) bulk, which is not occupied by the grains (air volume) (Oyedeji et al., 2021). The porosity of the beans was calculated from grain true density and grain bulk density according to Oyedeji et al. (2021) and Simonyan et al. (2009). Beans porosity was calculated to be 54.1%.

Assuming that the grain heater is represented by a bulk mass M_g, heated by the outer and inner surfaces of the grain hopper, the differential equation of the temperature variation inside the hopper can be written as:

$$M_g C_g \frac{dT}{dt} = AU(T_h - T) \qquad (1)$$

Where:

T is the instantaneous temperature of the bulk grain (^{o}C).

T_h is hopper wall temperature (^{o}C).

A is the surface area of the hopper walls (m^2).

U is the internal overall heat transfer coefficient of the hopper to grains (W/m^2 ^{o}C).

The internal heat transfer process is a mixture of conduction and convection processes due to the presence of air gaps inside the grain heating hopper and needs to be estimated. Convection becomes very weak in low-porosity systems and the heating process is dominated by conduction. The thermal conductivity of the grains ranges from 0.25 to 0.35 W/m^{o}C, for moisture content between 10 to 25%. A typical value of 0.3 W/m^{o}C is considered in the present work. The thermal conductivity of air is typically 0.025 W/m^{o}C, which is one order of magnitude less than that of beans.

Equation 1 can be directly integrated to obtain the temperature variation with time inside the grain heating hopper and consider the initial temperature of grains to be T_i at the start of the heating process (t=0) and the hopper wall temperature (T_h) temperatures to be constant during this period. The result of the integration can be written:

$$T_h - T = (T_h - T_i)\, e^{-t/t_o} \qquad (2)$$

Where the time scale t_o is defined:

$$t_o = \frac{M_g C_g}{UA} \qquad (3)$$

In equation 3, the effect of porosity on the effective specific heat is neglected due to the negligible mass fraction of air in the grain container. The time scale can be plotted against the overall heat transfer coefficient U as shown in **Figure 3**. As can be seen, the time scale drops exponentially with U. For high values of U the time scale approaches 10 min. In order to estimate the proper value of U, the experimental results shall be plotted versus the model results and the best value of U to match the experimental results shall be selected.

The surface temperature of hopper walls due to hot water circulation can reach 70^{o}C. The initial temperature of grains is assumed to be 30^{o}C and equation (3) can be plotted for different values of the heat transfer coefficient to observe the bulk grain behaviour.

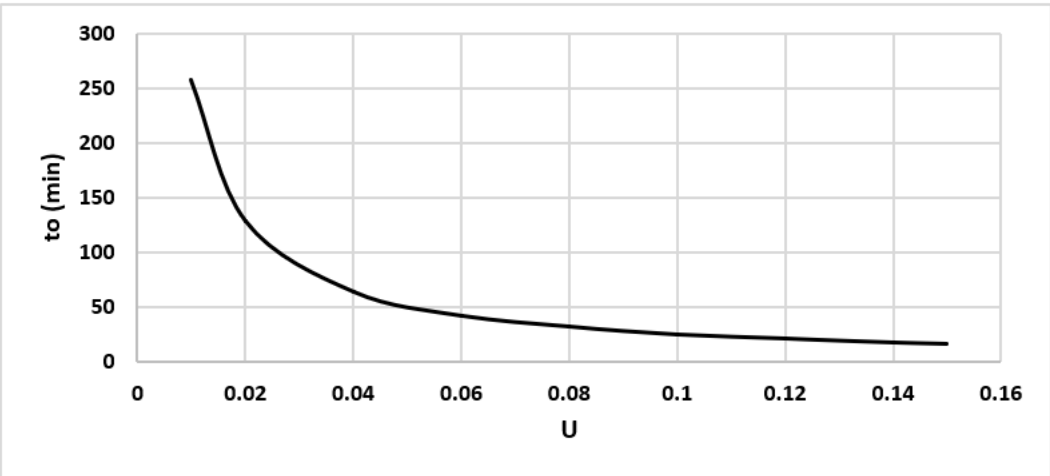

Fig. 3. Variation of two with U.

3.Insects and Experimental Design:

Callosobruchus maculatus (Coleoptera: Chrysomelidae: Bruchinae) was used in the present work. The insect colony was kept on broad beans (*Vicia faba* L.) for several years in an incubator in the dark at 28 ± 2^{o}C and 35 ± 2% r.h. in the Department of Entomology, Faculty of Science, Ain Shams University, Cairo, Egypt.

Experiments were conducted from 4th to 6th of March 2018 on the roof of the Faculty of Science, Ain Shams University, between 12.30 and 3 pm when the solar radiation was perpendicular to the earth. The experiment was set up to have three temperature regimes, starting at 45, 50, and 55, respectively, and lasting for 20 min. The 20 min time has been chosen based on previous data (Fawki et al., 2014), as 20 min exposure time was enough to kill all stages of *C. maculatus* under temperatures 52 to 64^{o}C. The grain hopper temperatures were recorded in three positions during the experiment: the inlet temperature of the inner coil, the inlet temperature of the outer coil, and grain temperatures. The grain temperature sensor was planted in the middle of the grains in one sector of the hopper. Three waterproof temperature sensors (version DS18B20, Future Electronics Egypt, Cairo, Egypt) and data acquisition (Multifunction I/O Device, USB-6008, 10 kSPS, 12 bit, 8 Input, 2 Output, 12 I/O, ± 10 V, DAQmx Device, National Instruments, Austin, Texas, USA) were used to record temperature readings. LabVIEW (Laboratory Virtual Instrument Engineering Workbench) programming software was used for data acquisition. Two sensors were fixed at the inlet of both inner and outer coils, and the third one was used to measure the temperature inside the grains when it was loaded into the tank during the experiment.

On each day of the system run, 3 kg of broad beans infested with 180 adult insects (males and females) were divided into different sectors of the hopper (approximately four sectors). Then the solar heater was switched on. The temperature sensors of the solar heater were adjusted to ensure that the hot water supplying the grain hopper was above 70^{o}C. The water flow in the grain hopper was adjusted by the water valve between the heater and the hopper. The water flow rate inside the inner coil was ≈12 ml/sec, and the flow rate inside the outer coil was ≈ 9 ml/sec. The grain heating system was allowed to run until the system reached the desired temperatures (45, 50, or 55^{o}C) for each treatment. Then, the water valve was closed to leave the infested grains subjected to different temperatures for 20 min. In the end, the bottom cover was opened to discharge the infested grains. In the bottom of the hopper beneath the grains, a circular carton sheet with a cut part was added to facilitate grain discharge from each sector separately. Infested beans were collected, and the mortality of adult insects was recorded after one hour in the lab. Insects were considered dead when they had no sign of movement when touched with a brush.

The experiment was planned to have three replicates for each temperature regime (45, 50 and 55^{o}C). However, because of technical problems, the grain heating system was run once for each desired temperature. A control group of infested beans with 180 adult insects (males and females) was kept in lab conditions at ± 2^{o}C and 35 ± 2% r.h.. Adult insects' morality (%) was recorded after one hour.

Faba beans' moisture content (m.c.) was measured before and after each heating runs using mini digital hygrometers. Three samples of 20 gm of treated beans were used for each heating run. Another three samples of untreated faba beans were used to determine the bean's m.c. before heating treatment. Unfortunately, the beans germination test and the more accurate grains m.c. tests could not be completed due to some technical problems.

RESULTS AND DISCUSSION

1-Hopper Heating Profile:

Temperature data of the grain hopper is shown in Fig. 4. The water in the outer and inner coils of the hopper had similar temperature profiles except at the start of the experiment (t<20 minutes) (Fig. 4). Water heats up in the outer coil with the highest heating rate of at the beginning of the experiment before the system reaches a steady-state temperature of 68˚C, the same temperature as hot water coming from the solar heater. The grain core temperatures had almost a constant heating rate throughout the experiment (Fig. 4). Grain heating time to reach the target temperature of 50°C is approximately 80 minutes.

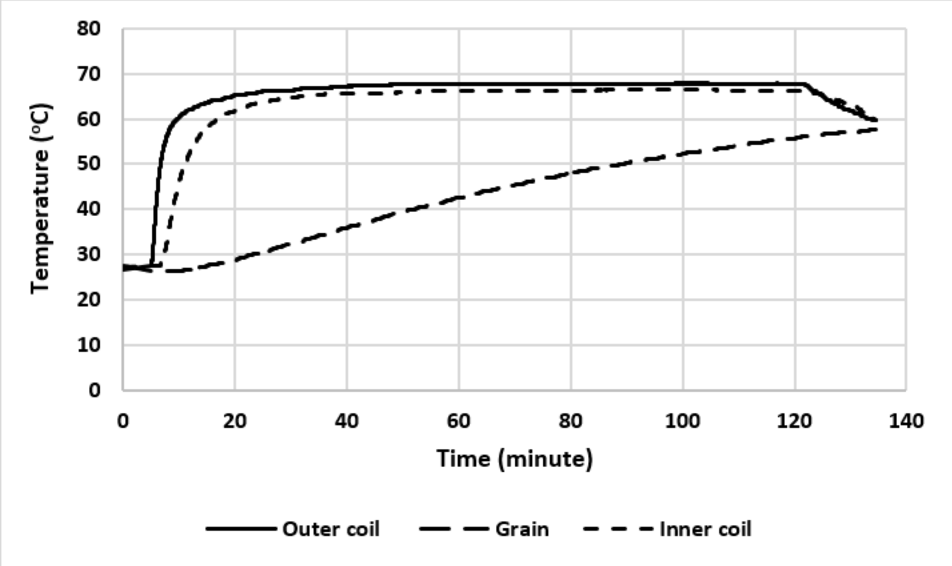

Fig. 4. Temperature measurements of the outer coil, grain and inner coil during the experiment.

Interestingly, the temperature profile of the grain bulk is similar to the thermal behavior of reinforced concrete walls after fire exposure in another study (Kang *et al.*, 2016). In the present work, the grain bulk center had much lower temperatures than the peripheral of the grains near the source of the heating coils. In Kang *et al.* (2016) study, the temperatures at the middle point of the concrete wall were lower than that at the peripheral part of the wall near the fire source.

The dimensionless temperature variation $(T_h\text{-}T)/(T_h\text{-}T_i)$ versus t/to is shown in Figure 5. The figure shows that using U=0.02 W/m^2 °C in equation 3 shows reasonable agreement between model results (equation 2) and experimental measurements. The small difference appearing in the initial time can be attributed to the fact that the hot surface in the experiment heats up gradually while in the model this temperature is assumed to be constant from the start of the experiment. The slope of the temperature variation predicted by the model is very close to the experiment after t/t_o=0.6. This agreement shows that it is possible to model the heating behaviour of the container using equation 2.

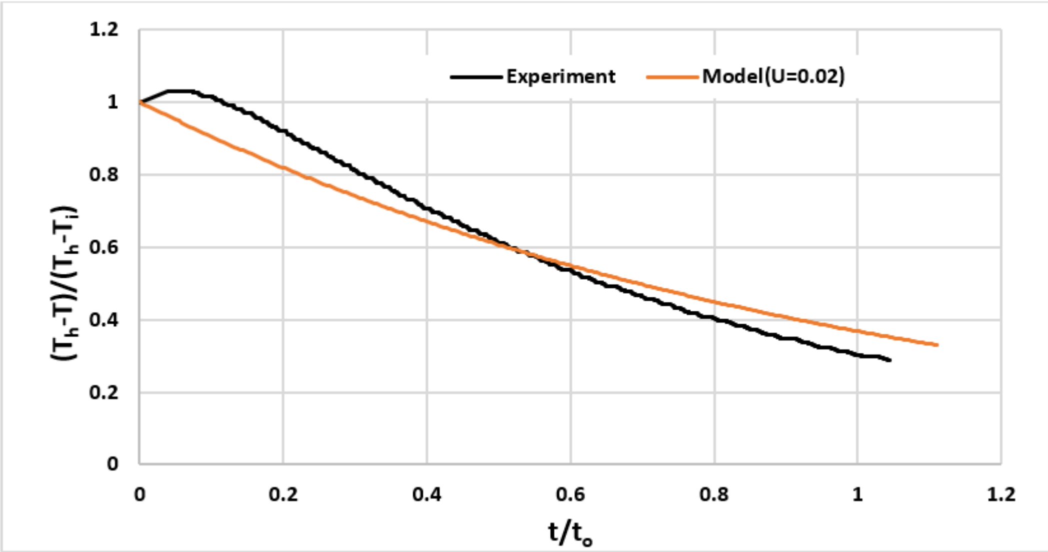

Fig. 5. Dimensionless temperature variation. Comparison between model results and experimental results.

2-Heating Effect on *Callosobruchus maculatus* and Faba Bean Quality:

Some insects were able to escape from the hopper during the 45 and 50°C heating treatments (Table 1). This was mainly because the cover at the bottom of the hopper was untight and insects tend to move from hot areas inside the hopper to cooler areas outside the hopper during the heating treatments (Jian, 2019). However, 36 out of the remaining adult insects in the hopper after grain-heating treatment were able to survive after one hour in the 45°C group, while all remaining insects in the hopper were dead after one hour in the 50°C group (Table 1). In General, the grain hopper was able to achieve complete *C. maculatus* adults' mortality within 115 min in the third treatment where the temperatures ranged from 55 to 57°C (Table 1). This range has been reported to be lethal for stored grain insects (Beckett *et al.*, 2007; Fawki *et al.*, 2022; Fields, 1992; Sutherland *et al.*, 1989; Zhao *et al.*, 2007). Interestingly, no insect was able to escape from the 55°C treatment, and no morbid insects were detected in all treatments.

Table 1: Number of dead insects, number of live insects, escaped and time required to reach the desired temperature range during the three experimental runs.

Temperature range (°C)	Heating time (min)	No. of dead insects	No. of live insects	Escaped insects
C (27)	0	0	180	-
45-51	82	124	36	20
50-54	78	138	1	41
55-57	115	180	0	-

A very important point is that the performance of the heater was sufficient to control stored grain insects under winter weather conditions in Cairo, Egypt. This implies that during the summertime (from June to August) the heater will be even more efficient and a shorter time will be required to reach insects' lethal temperatures. In March, the day temperatures range from 20 to 30°C, while over the summer they range from 30 to 40°C (Time and Date AS, 1995-2022).

This technique is a kind of high-temperature/short-time protocol that has been used for grain disinfestation (Mourier and Poulsen, 2000; Tang *et al.*, 2000). This method depends on using the best temperature and time combination to achieve complete insect mortality without damaging different foods and commodities used. *Callosobruchus maculatus* has been chosen as a model insect for this study, but the solar heating system could be used in thermal control for other stored grain insects as well. This prototype is an eco-friendly heating system that could be operated with different insects and grains/seeds combinations. Many thermal death data for stored grain insects and mites are available from previous studies (Tang *et al.,* 2007). These data will help set the target lethal temperatures for operating the heating system. Applying the mathematical model will facilitate determining the heating time required for each pest under different conditions/variables.

Faba beans m.c. before the experiment had an average of 51.5%, while after different heating treatments it had an average of 47.5%. Although the germination test for the beans has not been performed, similar temperature regimes have been reported to have no adverse effect on the grain viability of cowpea grains subjected to solar heating (Fawki *et al.,* 2014; Murdock *et al.*, 2003; Ntoukam *et al.*, 1997). Murdock *et al.* (2003) reported that heating up to 80^{o}C for 6 hours had no negative effect on cowpea germination. Another important parameter that should be considered is the color of the faba beans as high temperatures increase the darkening of the beans (Bello and Udoh, 2022; Nasar-Abbas *et al.,* 2009). Bean darkening after exceeding a certain limit will reduce the acceptance of the beans for human consumption (Bello and Udoh, 2022; Nasar-Abbas *et al.*, 2009), and this consequently will cause a considerable commercial loss (Bello and Udoh, 2022; Boxall, 2001). Faba bean has also been reported as a good source of animal feed. Both seed coats and split beans are considered a nutritive source for ruminant animals and poultry (Sherasia *et al.,* 2018). Solar heat disinfestation of grains/seeds as a source of animal feeds also needs to be investigated. Further studies are required to investigate the effect of solar heating treatment on different grain/seed quality.

Generally, going solar and green is one of the essential pillars of achieving the sustainable development goals of 2030 (SDGs) of the United Nations (United Nations, 2015). Therefore, there is a global concern about climate change and ways to mitigate the effect of greenhouse gases emission and the reduction of carbon footprint. The food sector and agriculture activity are responsible for 30% (IAEA, 2022) to 50% in some cases (Ministry of Environment (New Zealand), 2022) of greenhouse gases emission. The cost of food production from crop to the consumer is very high. At the same time, the cost of food production to fulfil human and livestock food demands is growing very fast. Therefore, reducing post-harvest loss indirectly increases food production, reduces the economic loss in the food chain, and reduces the carbon footprint of the agriculture sector. Recently, at the 27th Conference of the Parties of the United Nations Framework Convention on Climate Change (COP27), actions towards the 2030 agenda have been focusing on using renewable-based technology and Solar power in different sectors IRENA (2022). Globally, in 2022 the rate of implementation of solar photovoltaics has rapidly increased by 21-fold compared to its rate of implementation in 2010 (IRENA, 2022). At a global level, the cost of installing solar photovoltaics in 2021 has declined by 81% lower than the market cost in 2010 (IRENA, 2022).

Conclusion

The present grain solar heating system is a potential system for thermal disinfestation against stored grain pests. A critical equation is to keep the balance between the effective temperature/time combination to control insect pests and grain/seed viability. With the abundance of solar radiation in many nations, there is a growing trend to implement more solar thermal technologies in the agricultural and industrial sectors. One of the drawbacks is the cost of these systems. To overcome this issue, socio-economic studies are needed as part of a collaborative approach between, governments, private sectors, and investors. The present work shows that the heating behaviour of the hopper can be successfully modelled using the bulk heat transfer equation with the proper selection of the overall heat transfer coefficient.

Credit Authorship Contribution Statement:

Shams Fawki: Conceptualization, Methodology, Investigation, Resources, Visualization, Project administration, Funding acquisition, Writing-Original Draft, Writing-review & editing. Walid Aboelsoud: Conceptualization, Methodology, Visualization, Writing-review & editing. Ahmed M. R. Elbaz: Conceptualization, Methodology, Visualization, Experiment design, Mathematical model, Validation, Writing-Original Draft, Writing-review & editing. All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest: The authors declare no conflict of interest.

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