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Research article

Design, construction, and testing of passive type solar tunnel for maize grain disinfestations

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ABSTRACT

In this study, a solar tunnel of passive-type designed, constructed and tested for storage insect pest disinfestation. The designed solar tunnel was 1.9 m wide and 3 m long with the maize grain holding capacity of 150 kg, 300 kg, and 450 kg with 5 cm, 10 cm, and 15 cm layer thickness respectively. To evaluate the performance of the solar tunnel, maize grain infested with storage pests was kept in the solar tunnel with 5 cm, 10 cm, and 15 cm layer thickness for 4 consecutive days. During the study, the temperature and relative humidity profile of the air in the tunnel and the temperature in maize grain was recorded. Germination percentage and number of live insects were evaluated after each day of disinfestations. The highest temperature recorded in the solar tunnel was in the range of 64.6–67.6 °C during the study period. Complete disinfestations of the grain were obtained on the first day for 5 cm layer thickness and the second day for 10 and 15 cm layer thickness. The higher germination percentage was recorded for 15 cm layer thickness in all experimental days. Of all the treatments the combination of the layer thickness of 15 cm and two day disinfestations time were found to be the best combination for using the tunnel for maize grain disinfestations in terms of achieving complete disinfestations; maintaining germination capacity of the grain and time required to disinfect a large amount of grain.

1. Introduction

Grain crops are said to be the dominant source of nutrition for one-third of the world's population particularly in developing nations of sub-Saharan Africa and south-east Asia. They are important in Africa serving as a source of food, feed, and industrial raw material (Meseret, 2011). Among the grain crops; maize is one of the major staple food crops widely grown by smallholder farmers in Ethiopia. The smallholder farmers that comprise about 80 percent of Ethiopia's population are both the primary producers and consumers of maize (Liu et al., 2016). According to CSA (2021) report in 2021, out of 34.1 million tones of grain crops, cereal crops production covers 30.2 million tones 88.6% of the total production whereas maize covers 10.5 million tones (34.8% of cereal crops). Though the production of maize grain is going on advancing, postharvest losses caused by storage insect pests are one of the major constraints in Africa in general and Ethiopia in particular.

Nearly one thousand species of insects have been found associated with stored products in various parts of the world. Among many stored pest's weevils, bruchids, larger grain borer, and grain moths are the most notorious (Tefera et al., 2011a; 2011b). *Sitophilus zeamais* is among the major pests of stored maize in Ethiopia (Keba and Sori, 2013). Infestation by this weevil begins in the field, moves together with the grain to the storage place, and caused significant damage during storage (Demissie et al., 2008; Baidoo et al., 2010). Damage by *S. zeamais* causes food loss, increased poverty, reduce supply, and lower the nutritional values of grain, and market values (Keba and Sori, 2013). In Ethiopia, 20–30% of stored maize is lost to *S. zeamais* infestation, while 100% damage has been found in maize stored for 6–8 months in the Bako (Demissie et al., 2008).

Disinfestation of insects in grains is an important unit operation during the storage and handling of grains (Moirangthem and Baik, 2021). Synthetic chemical insecticides have been widely used for the control of pests of stored maize grain, particularly *S. zeamais* (Cherry et al., 2005). Their use can prevent loss of yield and reduce losses. They work quickly, which makes them suitable for use in emergencies and are the only remedy when crops are under immediate threat of infestation. However, there are - ever-increasing dangers from the dispersion of these chemical agents into the environment (Mbah and Okoronkwo, 2008). Their

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widespread use for the control of stored-product insect pests is of global concern to chemical residues in food, environmental hazards, and insect resistance to these synthetic chemical insecticides. For these reasons, it is important to look for residue-free and environmentally friendly insects pest control methods to minimize storage losses to minimize losses, enhance supply to ensure food security, and feed the ever-increasing population.

There are different non-chemical storage insect pest disinfection methods. Moirangthem and Baik (2021) well-reviewed details of the methods) and stressed that among many nonchemical methods, heat or thermal treatment is one of the methods to kill insect pests and inactivate viable eggs. Different thermal techniques such as Microwave, Radio-frequency, Infrared, Ohmic heating, can be used in the disinfection of food grains (Sirohi et al., 2021). They are rapid and residue-free methods of controlling stored grain pests (Qaisrani, and Beckett, 2003). However, they come with their specific own set of challenges, that affect the physicochemical properties of the grains being treated and high installation costs (Moirangthem and Baik, 2021; Sirohi et al., 2021). Furthermore using these technologies with energy sources from biomass and fossil fuels will result in greenhouse gas emissions that contribute to global climate change. However, solar energy is a sustainable and clean energy source that is widely accessible and can be utilized to organize more environmentally friendly systems in the future (Khanlari et al., 2020).

Technological advancements and use of solar energy for different purposes (drying, heating, disinfection) thermal energy storage (Selimefendigil and Şirin, 2021), and dehumidification of sewage sludge are research works and investment interests in the area. There are also efforts to enhance the performance of solar air collectors to increase the temperature of the solar driers for better efficiency (Sözen et al., 2020; Tuncer et al., 2020). Solar-based technologies are also in line with one of the Sustainable Development Goal of the United Nations (SDGs) (gaol 7 Affordable and Clean Energy). Apart from these studies and goals, studies showed that solar energy can be used as a means to disinfest soil to make it free from soil-borne diseases and aggressive weeds. This is mainly associated with the disinfection power of heat accumulated from solar radiation to inactivate potential microorganisms and seeds of weeds. However, so far there is limited information available on the disinfection power of the passive type solar tunnel technology against storage insect pests. Pre-storage infestation of harvested maize at the field level is the primary causal factor for significant reproduction and damaging impact of insect pests during storage. To avoid this, it is necessary to develop a mechanism to store insect pest-free grains. Live insects, their larvae, and eggs as biological entities can be killed with moderate heating without causing a significant impact on the quality of the grain. This can be achieved through the use of solar energy technologies like tunnel solar disinfectors for a large volume of grains to generate a sufficient amount of heat to kill insect pests and inactivate viable eggs. The technology is not expensive, can be constructed from locally available resources, and is environmentally sound. Therefore, this study attempted to design, construct and evaluate passive-type solar tunnels as a means to disinfect maize grains before storage.

2. Materials and methods

2.1. Study area

Design, construction, and testing of the solar tunnel were conducted at Jimma University College of Agriculture and Veterinary Medicine which lies between 36° 50′ E longitudes and 7° 42′ N latitude at an altitude of 1710 m above sea level (masl) with an average maximum and minimum temperature of 26 and 11 °C respectively. The average annual temperature is 20 °C. The area experiences an annual average rainfall of 1000 mm for 8–10 months. The germination capacity test of the maize grains and insect count was carried out at Postharvest Management laboratory, Jimma University College of Agriculture and veterinary medicine.

2.2. Design and construction of the solar tunnel

2.2.1. Design conditions and assumptions used

The solar tunnel used for this study was designed and constructed from locally available materials. The design calculations were based on the conditions and assumptions described in Table 1.

2.2.2. Collector length

With air that is changing in temperature, the heat flow rate associated with a temperature change and the thermal efficiency of the solar tunnel was determined by the Eqs. (1) and (2) respectively (Celma and Cuadros, 2009).

$$\dot{Q} = \dot{m} C \Delta t \tag{1}$$

Where:

$\dot{Q}$ = Heat flow rate in Js^{-1};
C = specific heat of air at Constant Pressure in J kg^{-1} K^{-1}
$\dot{m}$ = mass flow rate of air in kg s^{-1}
Δt = increase in temperature of air from the ambient in K.
But

$$\dot{m} = \rho a u$$

Where:

ρ = density of air in kg m^{-3}; t = time in s
u = Speed of air entering air into the solar tunnel in m s^{-1}
a = area of the openings through the air inter into the solar tunnel in m^2

Table 1. Design conditions and assumptions used in designing the solar tunnel.

No.	Parameters	Units	Assumptions
1	Average radiation	650 Wm^{-2}	Constant radiation for the area was used taking into account the average radiation of the area after measuring radiation for the whole day
2	Density of air	1.2 kgm^{-2}	Constant air density was used taking into account the average air density based on the ambient air temperature and relative humidity of the area
3	Area of the openings through which the air inters to the solar tunnel	0.1 m^2	Assumed to have minimum openings for air entrance and outlet
4	Specific heat of air at constant pressure	1000 J kg^{-1} K^{-1}	Constant specific heat capacity was used taking into account the average Specific heat of air at constant pressure on the average temperature and relative humidity of the air of the area at atmospheric pressure
5	Airspeed	0.08 m s^{-1}	Airspeed assumed constant throughout the time taking into account the average airspeed value
6	Expected Solar collecting efficiency of the solar tunnel	10%	Assumed constant value based on the information obtained from different passive solar tunnel dryers purpose (Brenndorfer et al.,1985; Simate and Cherotich, 2017)
7	Width of the tunnel	1.9 m	Assumed constant value based on the convenience to operate on the tunnel
8	The expected increase in temperature of air from the ambient	40 °C	Assumed based on the temperature required to kill live insects (Qaisrani and Banks, 2000; Mohammed-Dawd and Morallo-Rejesus, 2000)

$$\eta_c = \frac{\dot{m}C\Delta t}{\alpha\tau IA} \quad (2)$$

By substituting all the values in the equation the length of the tunnel is calculated to be equal to 3 m. The schematic view of the solar tunnel is shown in Figure 1.

A natural convection solar tunnel for maize grain disinfestations was designed and constructed. It has the capacity of holding 500 kg of shelled maize which was used in the experimental disinfestations test. The solar tunnel is 3 m long and 1.9 m wide and stands on 0.5 m high red brick support. It consists of a cover plate made of a low-density polyethylene sheet (transmittance. 85–87%) and an absorber plate made from a black HDPE sheet for absorbing solar radiation (Figure 1).

2.2.3. Experimental design and data analysis

The experiment was conducted with two factorials arranged on a completely randomized (CRD) design with three replications. The two factors were layer thickness with three levels (5 cm, 10 cm, and 15 cm) and time with four levels (one day, two days, three days, and four days) (Figure 2). Analysis of Variance (ANOVA) was done by using SAS software version 9.1. Mean separation was conducted using Turkeys' studentized range test (HSD) at a 5% level of significance.

2.3. Preparation of maize sample, rearing of maize weevils, and inoculation

For this study, Maize of variety (BH-660) was purchased from one lot of a given farmer and heat-treated in an oven (Leicester, LE67 5FT, England) at 60 °C for 2 h to kill live insects, larvae, and their eggs. The sample was assumed free from live insects and their viable eggs to use in subsequent study steps. The initial generations of maize weevils (*S. zeamais*) were obtained from maize market stores in Jimma town and allowed to reproduce further at room temperature in the Agricultural Entomology laboratory to obtain a large population of weevils (*S. zeamais*) reared under the same condition. Maize grains not previously treated with any insecticide were used to rear the insects. Then 10 active weevils were inoculated per 10 kg of maize grain; mixed and stored for 30 days to attain equilibrated condition and relatively high level of natural infestation. The constructed solar tunnel was evaluated in terms of its efficiency to destroy pests of all stages of development during the testing period. Maize grains that were not treated with heat were used to determine the effect of disinfestations with a solar tunnel on seeds germination capacity.

2.4. Data collected

2.4.1. Temperature, relative humidity and solar radiation measurement

Product temperature, the temperature of the air in the solar tunnel, and the temperature of the ambient were recorded in a 30 min interval using a data logger (Agilent, Model 34970A, and the USA). The relative humidity of the air in the solar tunnel and of the ambient was recorded in a 30 min interval using a data logger (Testo 174, Germany) during the experimental test. A pyranometer (model SP Lite2, Germany) was used for solar radiation measurement at 30 min intervals.

2.4.2. Number of live weevils

From the collected sample, the number of live insects was identified and counted and percent adult mortality was determined as per the method described in Parugrug and Roxas (2008) as indicated in Eq. (3)

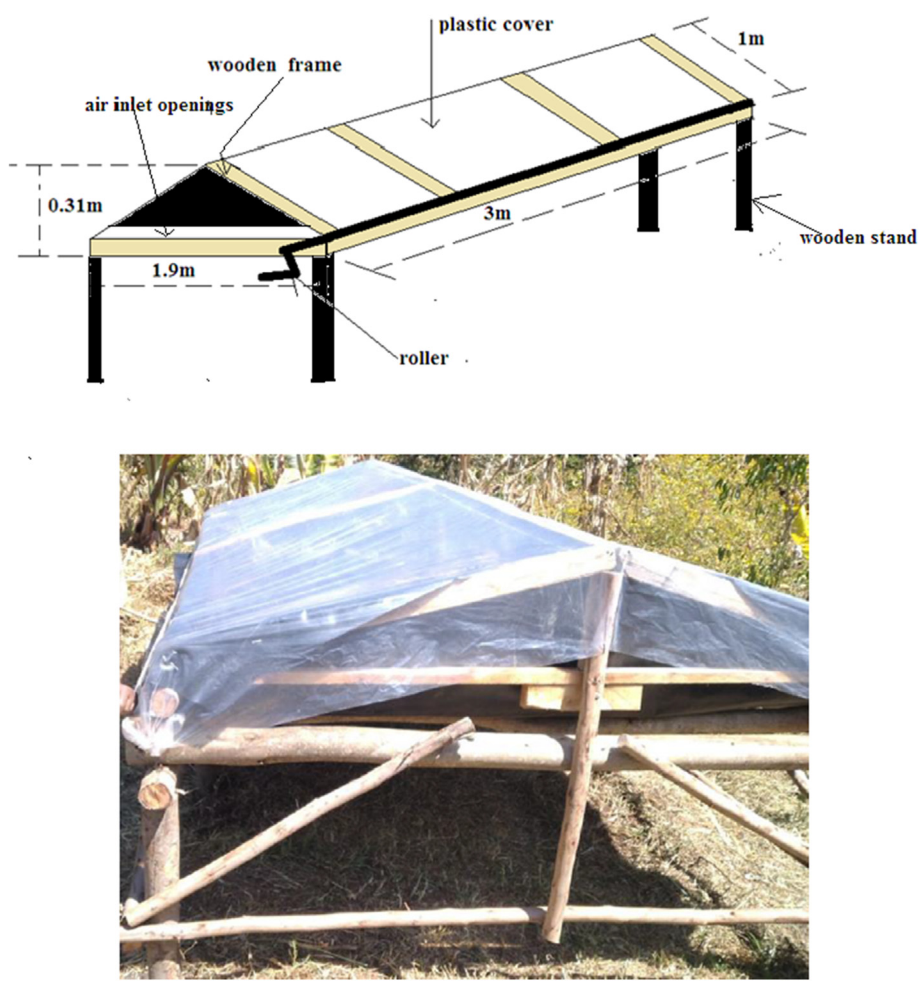

Figure 1. Schematical pectoral view of the constructed solar tunnel disinfector.

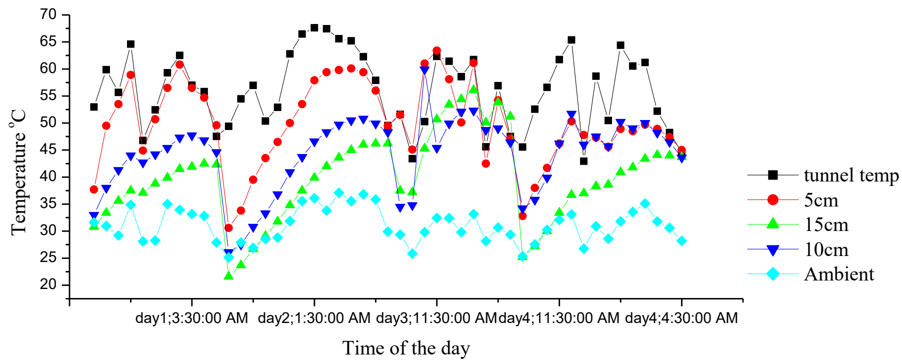

Figure 2. Variation of the temperature of ambient air, the air in the solar tunnel, and temperature inside the bulk of the product with different layer thickness through time for days 1–4.

$$Live\ \ Weevils\ \ (\%) = \frac{Number\ \ of\ \ live\ \ weevils}{Total\ \ number\ \ of\ \ weevils\ \ in\ \ a\ \ sample} \times 100 \quad (3)$$

2.4.3. Germination percentage determination

To carry out the germination test, one hundred randomly selected seed samples were placed in Petri dishes containing moistened soft paper and kept at 30 °C in an incubator (Model MJX-150B, China). The number of germinated seedlings from each Petri-dish was counted and recorded after 7 days of planting. The percentage of germination was computed as described in Zibokere (1994), as follows:

$$Germination(\%) = \frac{Number\ \ of\ \ seeds\ \ germinated}{Total\ \ number\ \ of\ \ seeds} \times 100 \quad (4)$$

3. Results and discussion

3.1. Temperature, relative humidity, solar radiation, and layer thickness

Experimental trials on the solarization of maize grain to destroy maize weevils in the designed solar tunnel with solar radiation were done in Jimma Ethiopia in the month of June 2021. The minimum and maximum values of the air temperature recorded in the solar tunnel during the experimental trial from 10:30 am to 4:30 pm were 46.7 °C and 64.6 °C on day one; 49.4 °C and 67.6 °C on day two; 43.4 °C and 65.2 °C on day three and 42.9 °C and 65.3 °C on day four respectively (Figure 2). However, the maximum ambient temperatures recorded during the trial were 35 °C, 37.1 °C, 33.2 °C, and 35.1 °C on days one, two, three, and four respectively. This fluctuation in the air temperature in the solar tunnel could be due to the fluctuation of the solar radiation and weather conditions with the time of the day (Figure 2). The temperature rise close to higher temperature levels observed between midday to mid-afternoon time and showed a decline as indicated in Figure 2 after mid-afternoon.

Regardless of the equivalent air temperature at which the samples are exposed in the solar tunnel, variation in product temperature was observed for maize grain samples with different layer thicknesses. The experimental trial showed that layer thickness affects the product temperature. From the temperature data, it was observed that higher product temperature was recorded for thin layer thickness (5 cm) and lower product temperature was recorded for thick layer (15 cm). During the experimental trial, the maximum product temperatures recorded were 63.4 °C, 59.9 °C, and 56.1 °C in the layer thickness of 5 cm, 10 cm, and 15 cm maize grains respectively (Table 2).

Studies indicated that stored grain pests can be killed instantly with temperature exposure above 65 °C and takes a few hours to 50 °C and days at 45 °C (Qaisrani and Banks, 2000). Different researchers reported the effectiveness of dry heat treatment to destroy maize weevil at all stages of development. Mohammed-Dawd and Morallo-Rejesus (2000) reported that all eggs and adult weevils were killed following exposure of infected maize of 13% and 16% moisture to 60 °C for 2 h. Other studies

Table 2. Maximum product temperature recorded in the different layer thicknesses of the maize grain during the experimental trial in the solar tunnel.

Experimental time	Layer thickness and temperature inside the grain		
	5 cm	10 cm	15 cm
Day 1	60.8 °C	47.7 °C	42.5 °C
Day 2	59.8 °C	49.7 °C	43.6 °C
Day 3	63.4 °C	59.9 °C	56.1 °C
Day 4	50.3 °C	51.7 °C	44.1 °C

also showed that a possibility to achieve 100% immediate mortality of maize weevils after treatment at 60 °C, 70 °C, and 80 °C (Ferrari Filho et al., 2011). Therefore based on the report on the literature on the survival and reproduction temperature of maize weevils; the temperature ranges attained in the designed and developed solar tunnel could be sufficient enough to kill maize weevils.

The relative humidity of air in the solar tunnel and of the ambient air during the solarization experiment is also indicated in Figure 3. It was observed that on the first day of the experimental trial the relative humidity of air in the solar tunnel was higher than the ambient air regardless of the higher temperature recorded in the solar tunnel than the ambient. This increase in the relative humidity of the air in the solar tunnel might be because as the temperature of the air in the solar tunnel increases it could enhance the evaporation and accumulation of water vapor inside the tunnel. However, starting from day two to four relative humidity of air in the solar tunnel showed a decreasing trend corresponding with the increasing trend of the temperature of the air in the solar tunnel. The decline might be associated with the migration of the moisture from the structure to the ambient environment.

The maximum solar radiation recorded during the experimental trial was 1050.77 W/m^2 (day one), 1129.23 W/m^2 (day two), 1038.46 W/m^2 (day three), and 984.61 W/m^2 (day four) at noon on (Figure 4) with an average maximum value of 1050.8 ± 59.7 W/m^2. The collector efficiency obtained from the designed solar tunnel ranged between 5-31% at different times of the day during the experimental period (Figure 5). However, there are reports to increase the efficiency of solar tunnel driers by modifying the structure of the drier collector. Experimental findings indicated in recent works (Sözen et al., 2020; Tuncer et al., 2020) showed that through different modifications the thermal efficiency can be increased significantly to overcome the limitation for rapid and efficient drying as well disinfections.

3.2. Effect of exposure time and layer thickness on live weevils

Table 3 shows the counted number of live weevils in the maize samples disinfected in the solar tunnel from day 1 to day 4. After the first day of disinfestations, the numbers of live insects counted per 250 g

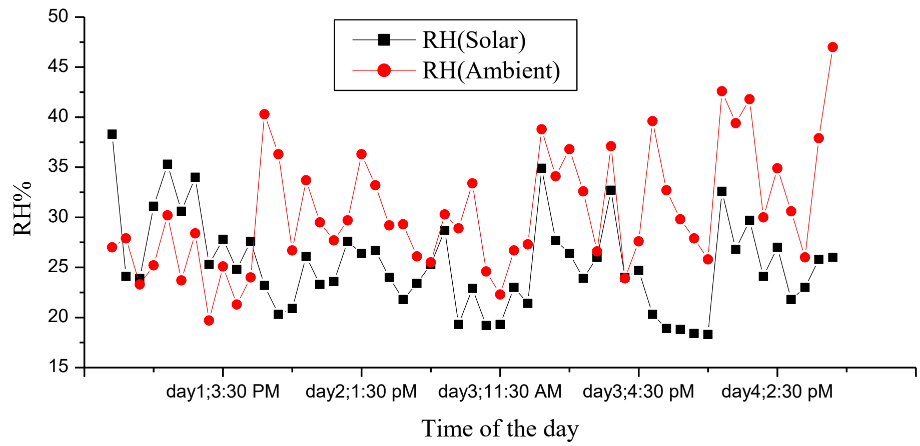

Figure 3. Variation of relative humidity of ambient air and air in the solar tunnel with time during the experimental trial.

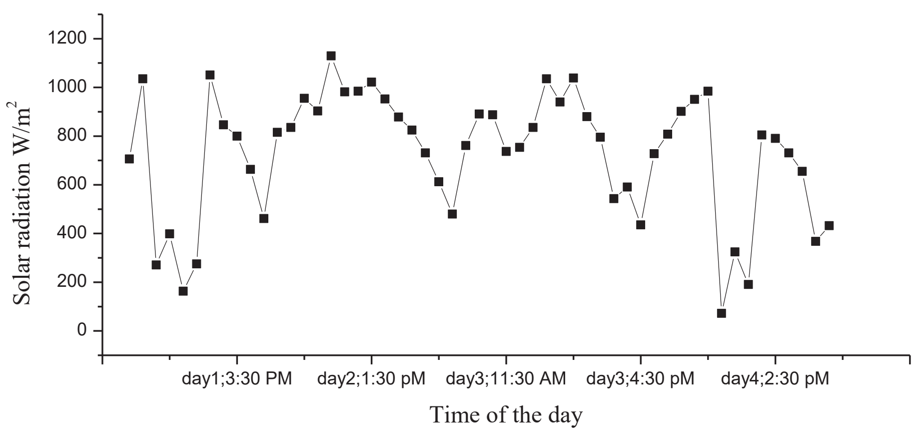

Figure 4. Variation of Solar radiation with time during the experimental trial.

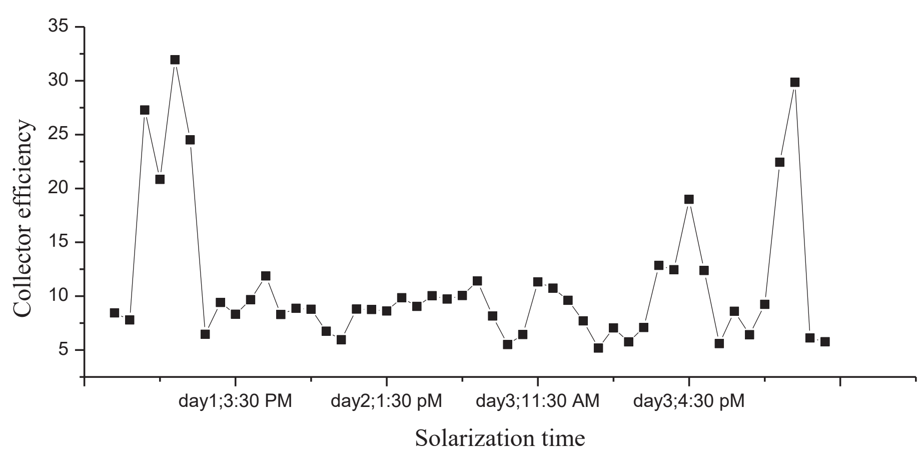

Figure 5. Collector efficiency of the solar tunnel at a different time of solarization.

sample were 0, 1, and 1 in 5 cm, 10 cm, and 15 cm respectively. The result shows that with a decrease in layer thickness and extending the treatment time the effectiveness of the solarization increased. The complete killing of the treatment at 5 cm layer thickness in the first days might be due to high product temperature (60 °C) (Table 2 & Figure 3) which could contribute to the accumulation of heat and its killing power. This is in agreement with the report of Ferrari Filho et al. (2011) who stated that heating temperatures above 50 °C have killing power for insects. After two days of disinfestations, no live insects were counted in the maize samples taken from all layer thicknesses. This shows that the accumulation of higher inactivation temperature for subsequent days during the day's time could contribute as a means to make grains field infestation free before storage. The inactivation effectiveness of dry heat treatment against weevils and their eggs is also reported by (Mohammed-Dawd and Morallo-Rejesus, 2000). The authors indicated that exposure of eggs and adult weevils to 60 °C for 2 h at different moisture levels results in their complete inactivation. The potential and benefits of non-chemical methods of inactivation methods of storage insect pests are well summarized in Moirangthem and Baik (2021). In addition to methods indicated in the review paper, the method indicated in this

Table 3. Number of live insects per 250 gm sample.

Time	Depth	Live
Day 0	–	10
Day 1	5 cm	0
	10 cm	1
	15 cm	1
Day 2	5 cm	0
	10 cm	0
	15 cm	0
Day 3	5 cm	0
	10 cm	0
	15 cm	0
Day 4	5 cm	0
	10 cm	0
	15 cm	0

study can also be used as one of the non-chemical methods for disinfection against field infestation particularly in resource-limited countries.

3.3. Effect of exposure time and layer thickness on germination capacity of maize

Heat accumulation during the solarization of maize grains could affect the viability and germination capacity of the seeds. This can be affected by exposure time to the heat and layer thickness of grains during treatment. A statistically significant difference ($p \leq 0.05$) was observed on the effect of exposure time and layer thickness on the germination percentage of maize (Table 4). It was observed that due to the increase in temperature of the air in the tunnel, the germination percentage of the grain decreased immediately after solar tunnel disinfestations; and this decrease in germination capacity increased over the treatment time. Asemu et al. (2020) also reported a higher germination percentage for shorter drying time (thin layer drying) than longer drying (thick layer) in bubble solar drier as the thicker layer drying takes longer exposure (5 days) than thin layer grain to be dried (2 days). This might be associated with a low or slow accumulation of heat for a bigger loading density.

For layer thickness, a direct relationship was observed with the germination capacity of the grain. The higher germination percentage was recorded from maize with 15 cm while the lower was recorded from the maize with 5 cm after solar tunnel disinfestations during all exposure times. This may be due to the higher product temperature recorded in the thin layer (5 cm) than the thick layer (15 cm) (Table 3). This result shows that exposing maize grain to more accumulation of heat with more exposure days results in a decrease in germination capacity. As indicated in Table 4, the germination capacity of maize decreased from 99 % before treatment to less than 90% on day four. Abdalgawad et al. (2018) also indicated that the potential negative effect of solar tunnel drying temperature on the germination capacity of maize grains.

4. Conclusion

From the experimental study, it was observed that high temperature and lower relative humidity could enable to inactivate weevils of maize from field infestation due to accumulation of heat from solar irradiation and migration of moisture from the insect pests at lower relative humidity. Solar disinfection as a means to inactivate maize weevils enables the storage of insect pest-free grains at the start to minimize the reproduction potential and damaging impact of the pests during storage. The lower the thickness could assist fast the inactivation in a single day. This could be used for a small volume of grains. However, for large volumes, thicker layers for multiple days of exposure are recommended to attain the intended goal. Storage of insect pests' free grains should be complemented with insect pests' free storage structure to avoid re-infestation of the grains. This work was conducted in the month of June considering relatively the worst-case scenario for solar radiation intensity. Results in this study showed that better results in a shorter time could be achieved during the main harvesting months in the area (November–January) when their intensity of solar radiation is high. Exposure of the grains for longer days at lower thickness significantly affects the germination capacity of the grains. It is better to use this method of disinfection to treat grains for consumption purposes than as a seed source. Producers should have an alternative seed storage mechanism or source for the next season. Solar disinfection of grains against field infesting insect pests will enable the protection of the stored grains against storage insect pests and minimize storage losses of grain crops. In addition to another novel, non-chemical treatment methods grain solarization could also be used as one of the physical treatment methods to control the impact of insect pests. The technology can be constructed from locally available materials at less cost to exploit its benefits by farmers in Sub-Sahara Africa countries where solar intensity and duration are abundant. However, this work demands further investigation from better efficiency, affordability, and scalability for different scales of production. There is enough information on the application of solar technologies to produce low moisture or dried agricultural products. Technological advancements in the drying area can be customized and applied to similar areas for better efficiency and cost.

Table 4. The effect of exposure time and layer thickness on germination percentage (Mean ± sd) of maize.

Exposure time	layer thickness (cm)	Germination (%)
Day 1	5	$91.7^{cbd} \pm 1.53$
	10	$95.0^{b} \pm 1.00$
	15	$98.70^{a} \pm 0.47$
Day 2	5	$91.7^{cbd} \pm 0.58$
	10	$93.3^{cb} \pm 0.58$
	15	$95.0^{b} \pm 2.00$
Day 3	5	$85.0^{fg} \pm 1.00$
	10	$88.3^{fed} \pm 0.58$
	15	$90.0^{ced} \pm 1.00$
Day 4	5	$80.0^{h} \pm 0.00$
	10	$83.3^{hg} \pm 1.15$
	15	$86.7^{feg} \pm 2.31$
Day zero	99 ± 0.81	
CV	1.32	
LSD	3.5	

Superscript letters show the significance differences between the treatments.

Declarations

Author contribution statement

Obsuman Damena; Lelise Tilahun; Chala G. Kuyu; Yetenayet Bekele; TizazuYirga; Tilahun A. Teka; Demelash Hailu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data associated with this study has been deposited at Jimma University College of Agriculture and veterinary medicine Library repository.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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