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Research Article

Enhancing Efficiency of Solar Heater Box with Linear Actuator for Maximizing Solarization

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Abstract: Worldwide, stored grain pests are massively infesting most stored crops and their by-products. The main losses are due to infestation of these pests occurring on various carriers just prior to harvest, during storage or shipping. Methyl bromide and phosphine fumigation have been widely used for phytosanitary treatment of stored grains but are recognized as highly effective in depleting ozone, and similarly, residue-free grains are important for thermal disinfection. Solarization is one of the best ways to manage and disinfect crops, the traditional solarization methods are already practised by farmers but are inefficient to kill all stages of pests and require additional land exposed to the sun. In this work, thermal disinfection systems using solar heaters are proposed, designed, and developed to offset the actual lethal heat window. For the experiment work, the solar heater boxes were constructed in an octagon shape with 135^{o} at the base for trapping maximum heat inside the solar the heater box. The characteristics of the proposed system proved simpler, faster, and inexpensive but equally effective to achieve the desired results in terms of heat generation and seed moisture.

Keywords: Solar Heater Boxes, Chickpea Grains, Temperature, Moisture, Seed Volume.

1. INTRODUCTION

Due to increasing population, food consumption is always on the rise globally, where the cost of food has reached new high scales, resulting in food insecurity, particularly in underdeveloped countries [1]. In developing countries, grain loss is significant because of inadequate post-harvest management knowledge and technology, improper storage facilities, and other factors. Around 20-30% losses of grains are recorded from most of the African countries [2]; and further 10 to 30% to other parts of the world [3]. Before storage of seeds, drying is a widely explored method for longer shelf life of agricultural products [4]. Mainly, it involves removing moisture from food materials to a safe level, slowing down the action of enzymes, bacteria, yeasts, and molds, and preventing insect damage. Grain needs to be dried 13% for long-term storage and 15% for short-term storage to be stored safely to keep the quality and quantity of grains [5]. Quantity losses happen when the grain is consumed by various arthropod insect pests, whereas quality losses show up as a reduced economic value of the crops or a decreased market worth of the product [6]. This results in decreased nutritional value, decreased seed germination, increased moisture, free fatty acid levels, decreased pH, loss of protein contents in food grain and existence of various protozoa that may cause dysentery and typhoid [7]. Approximately, 20,000 species are identified as pests of stored products [8] and estimated to destroy

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about one-third of the global production of food that is worthy of more than 100 billion dollars [9]. However, the performance of insecticides over the past few decades has made them widely accepted for use against a variety of pests that affect agriculture and public health. Using pesticides frequently has several negative effects, including the recurrence of pests, toxicity to mammals and non-target animals, notably beneficial for insects, environmental degradation, and the emergence of resistance [6]. Methyl bromide fumigation has been widely employed to treat stored grains for phytosanitary reasons, however the US Environmental Protection Agency (USEPA) has acknowledged that it has significant consequences on ozone depletion [10]. Therefore, alternatives to methyl bromide are required for all postharvest applications [11]. Insect resistance to phosphine and market demands for residue-free grain has increased the importance of heat disinfestations [12]. By adopting modern techniques in storage systems, grain losses can generally be low in the intermediate stage of the supply chain. A sustainable way to enhance grain supply, reduce the strain on natural resources, and help farmers on a wide scale is by reducing post-harvest losses of grains, especially in developing nations. It will surely resolve hunger and improve farmers' livelihoods.

Traditionally, agricultural commodities like grains, fruits, and vegetables are left to dry out in the sun on surfaces like compacted dirt, mats, concrete floors, and roadways. Solarization is one of the most reliable practices for seed disinfection for various noxious store grain insect pests. Such management of store grain pests is more successful, particularly in tropical and sub-tropical countries where there is a lot of sunshine throughout the year. But, to accommodate the world's expanding population, agricultural fields are being turned into residential and commercial sectors, which reduces the amount of land available for crop cultivation. Furthermore, applying this technique results in successful drying but exposes the agricultural products to contamination from dirt, dust, insect infestation, and loss from birds and other animals [4]. In addition, there is a risk that cereal grains and other products may be contaminated with aflatoxin. In this regard, numerous studies have been undertaken on the natural convection of solar drying for agricultural products [13-15]. For successful pest management particularly for store grain pests, use of solar energy with specified materials, tools and techniques achieved a certain lethal dose of heat without affecting the seed quality [16] but still require further improvement for maximum seed volume and efficiency. However, the prime aim of this proposing work is to trap and retain the solar thermal in a new constructed solar heater box installed with motorized machine to acquire lethal heat level of 50-62^{o}C for less than 1 hour [17] to disinfect the store grains from insect pests without damaging the grains quality.

2. MATERIALS AND METHODS

2.1 Design and Construction of Octagonal Solar Heater Boxes

Previously, solar heater boxes were constructed with an inverted pyramid shape and an obtuse base angle of 118^{o} which had proved to be more effective in capturing more solar energy [18 -20]. In the present study, a slight adjustment was made to the overall design of the solar heater box composed of an acrylic sheet of 2 mm thickness. The design of the solar box was an octagon in shape with 135^{o} at the base for trapping much better heat inside. According to the longitude and latitude of an experiment for capturing the most solar radiation, the angle N-S for the upper side of the boxes was 45^{o}. The total height of solar heater box was 92 cm, and the top face and base measure 40×40 cm^2 in size. For maximum heat absorption, the walls of the boxes were painted with black paint on both the inside and the outside. To save heat losses from solar boxes by conduction and convection, the Styrofoam sheet of 10mm was attached outside the boxes because it is an insulator that contains bubbles filled with air. Later, aluminum foil was adhered to the outside of solar boxes with glue to maximize solar radiation reflection, as previously reported by Masood et al., [21] for the seed thickness of 2 kg. The present experiment consists of different volumes of seeds for testing the similar or better efficiency of the designed solar heater box.

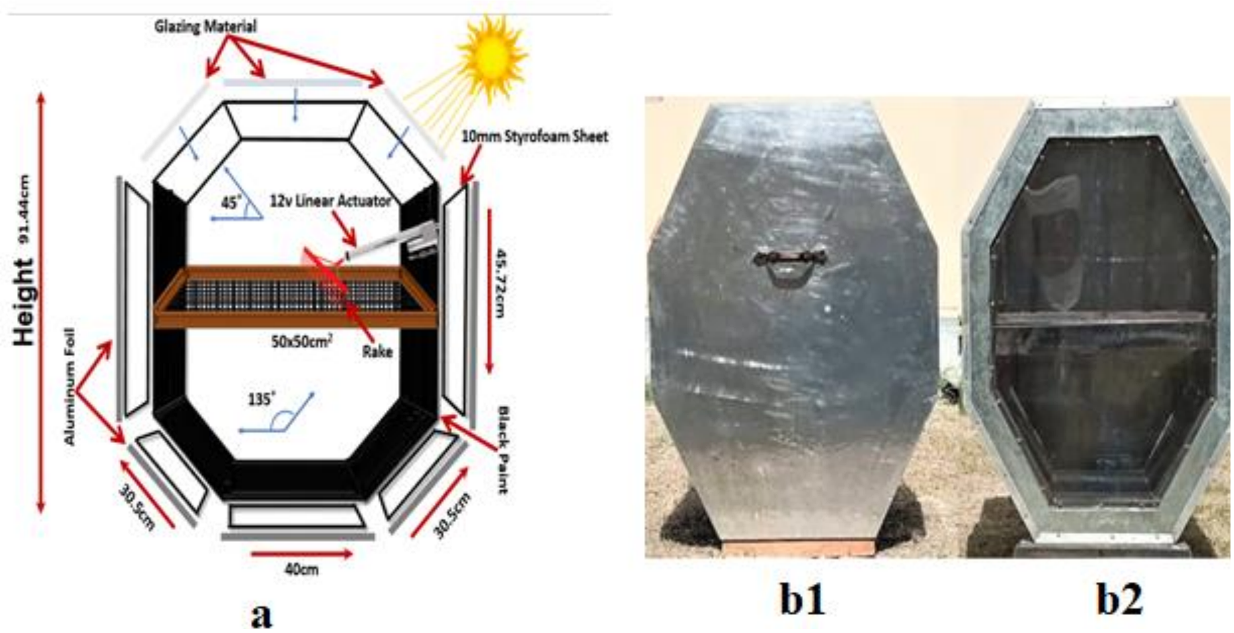
For heat penetration and retention inside the solar box, the face and half of the arms of the boxes were covered in glass. The inner and outer shapes of solar heater boxes are shown in Figure 1 (b1 and b2). In the first experiment, a total of 5 kg grains were placed on the tray (50×50 cm^2) containing holes that allow temperature penetration from all directions. To allow heat to enter from all sides, the tray is fixed in the center of each box at a perpendicular height.

1.2 Recording of Temperature and Seed Moisture in Solar Heater Box

Temperature and seed moisture in solar heater box were recorded by mini portable digital data logger (16000 points recoding capacity, 40°C~+85°C Model: Elitech RC-4HC; China) assembled with external thermal sensor (thermocouples) as shown in Figure 2. The data after recording was exported in MS-excel via data management software 5.16000 data recording capacity (record interval=10s~24hrs adjustable) in hp laptop for further review and analyzation. A sharp pointed sensor needle was inserted inside the seeds to know the penetration of temperature and moisture in solar heater box as shown in Figure 3. The thermal sensor was placed between the seeds at random depths to record the temperature and seed moisture with data loggers [21]. The different seed volumes such as 5, 10, 15, 22, 30 and 40 kg were placed inside the solar heater box. The temperature readings were set auto to take at every 15 minutes of each time interval. The ambient temperature was also recorded with digital thermometer (°C). The exposure time for experiment was 6 hours starting from 9.00 am to 3.00 pm. To increase the quantity of grains inside solar heater box, the efficiency of solar heater box was better enhanced through installation of a 12v linear actuator assembled with a wooden log (saw tooth like comb) fitted in Solar Heater Box as shown in Figure 4. Through a 12v linear actuator, the temperature in the solar heater box was kept constant at various grains volume by rotating the seeds inside box. The H-bridge motor driver regulates the linear actuator's direction and speed. Using an Arduino UNO micro-controller and C++ programming, a linear actuator's stroke automatically ceases after extending and retracting continuously for 10 minutes [21].

2.3 Data Analysis

The temperatures recorded in the solar thermal box for each 60 minutes exposure time, for seven days, were evaluated with the (RCBD) method using analysis of variance (ANOVA) in statistical analysis software (Statistic 8.1). The data loggers and thermocouples were configured to collect temperature data, and the relationship between temperature measurements taken at 15 minutes intervals within the solar thermal box and exposure time was examined using regression and coefficient correlation analysis. Temperature trend data were transformed prior to regression analysis. ANOVA



a b1 b2

Fig.1. Design and construction of Octagonal solar heater box (a) animated picture of box showing all the measurement, design, and structure (b1 and b2) original pictures inside and outside of box used for experiment [21]

Fig. 2. Data logger and digital thermometer for recording temperature and Humidity [21]

Fig. 3. Recording temperature and seed moisture at different depths using pointed sensor needle [21]

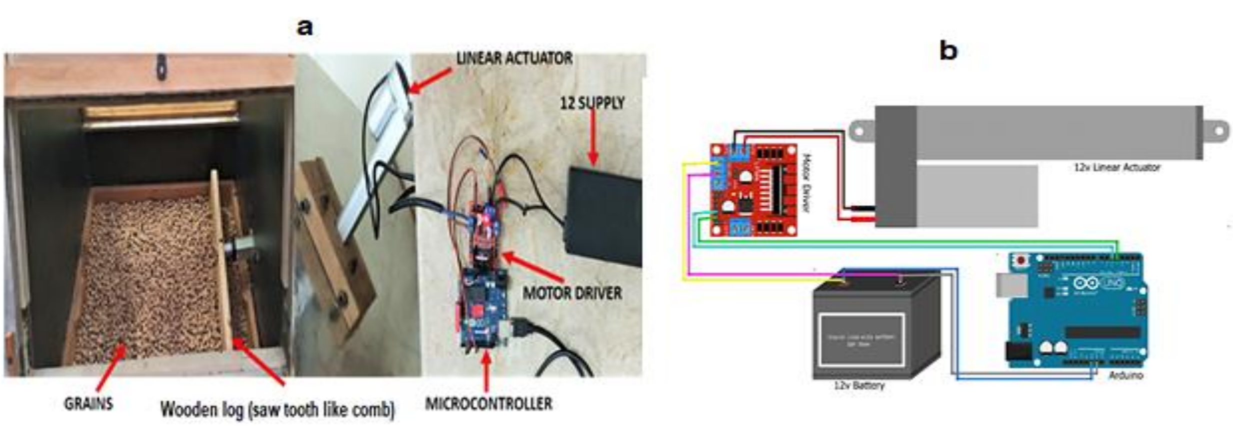


Fig. 4. Prototype (a) and circuit diagram (b) showing linear actuator assembled with wooden log for betterer retention of temperature and reduce moisture between grains inside solar heater box [21]

with RCBD was used to analyze data on the effect of seeding rate on optimal solar heating boxes, meanwhile, student *t* test for comparing seed moisture inside solar heater box with and without linear actuator was used. The least significant difference LSD (P=0.05) was used to demonstrate the heat trapping capacity of the solar heater boxes individually.

3. RESULTS AND DISCUSSION

3.1 Data Analysis of Different Solar Heater Boxes using 5kg Seed

The results regarding the temperature trapped inside the solar heater box was significantly different ($P<0.05$) with and without application of linear actuator as shown in Table 1. The maximum mean temperature of 43.35±0.89 °C was recorded in the first hour of observation in linear actuator as compared to the solar heater box without linear actuator. Meanwhile, the ambient temperature was quite lesser 29.48±0.32 °C. With time, the intensity of ambient temperature moderately raised up to 36.33± 0.68 °C in the last hour of observation (360 minutes), but the intensity of seed temperature recorded in solar heater box with linear actuator was the highest (78.11±0.84 °C) in comparison to seed temperature (63.21±6.02 °C) in solar heater box without linear actuator. Thus, the solar heater box with and without linear actuator successfully trapped the enough seed temperature inside the box as compared to ambient temperature. The present study was conducted after designing an octagonal solar heater box to obtain optimal results for capturing the maximum amount of solar radiation that can be detrimental to pest control of stored grains as (above 60 °C) with retention of 1 hour which is quite lethal for all stages of store grain pests [22]. Thus, the solar heater box with and without linear actuator successfully trapped the enough seed temperature inside the box as compared to ambient temperature. It has been previously well studied that for an effective structural heat treatment, the temperature must be maintained above 50°C for at least 24 hours [23]. Controlling arthropod pests by using high temperatures (above 50 °C) to disinfect products and/or structures is an environmentally friendly approach to protect stored products [19, 22, 24]. Thus, these arguments are clear evidence for the success of this study as with or without linear actuator, the designed solar heater box trapped enough heat energy that would be environmentally friendly for keeping grains after their harvest.

The seed moisture with temperature was also found varied ($P<0.05$) in solar heater box with and without linear actuator at different intervals as given in Table 2 in comparison to control seed moisture. In very first hour of experimental period (60 minutes), seed moisture (%) was maximum (62.32±0.6 %) in control condition whereas seed moisture recorded in the solar heater box without linear actuator was 45.89±1.56 % and with 39.74±1.97% with significant difference. With time, the seed moisture

Table 1: Record of temperature with and without linear actuator in solar heater box

Time (minutes)	**Temperature (°C) of solar heater box**		**Ambient temperature (°C)**
	with Linear Actuator	**without Linear Actuator**	
60	43.35±0.89^{a}	39.95±1.66^{b}	29.48±0.32^{c}
120	49.13±1.11^{a}	43.23±2.52^{b}	31.65± 0.44^{c}
180	52.00±1.30^{a}	45.52±3.49^{b}	33.32± 0.48^{c}
240	61.41±1.53^{a}	51.69±6.55^{b}	34.48± 0.49^{c}
300	69.51±1.67^{a}	56.99±7.10^{b}	35.40± 0.55^{c}
360	78.11±0.84^{a}	63.21±6.02^{b}	36.33± 0.68^{c}

The mean temperatures (Mean ± SE) were separated with least significant difference (LSD) at $p<0.05$ and represented by different letters within the same line.

Table 2. Record of moisture with and without linear actuator in solar heater box

Time (minutes)	**Moisture (%) of grains in solar heater box**		**Seed moisture (%) in control**
	With Linear Actuator	**without Linear Actuator**	
60	39.74±1.97^{a}	45.89±1.56^{b}	50.42±1.11^{c}
120	30.34±1.90^{a}	38.75±2.10^{b}	46.53±1.95^{c}
180	22.55±1.10^{a}	36.18±2.00^{b}	42.00±1.81^{c}
240	17.20±1.95^{a}	29.64±2.09^{b}	38.14±1.62^{c}
300	14.15±1.00^{a}	24.73±3.08^{b}	35.67±1.2^{2c}
360	12.01±1.8^{2}a	19.14±3.1^{8}b	29.69±2.21^{c}

The mean moistures (Mean ± SE) were separated with least significant difference (LSD) at $p <0.05$ and represented by different letters within the same line.

reduced in all treatments, but the reduction of seed moisture was the lowest 12.01±1.82 % in solar heater box with linear actuator and lower 19.14± 3.18 % without linear actuator at the end of experimental hours (360 minutes). Thus, these results show that the application of linear actuator successfully reduced the maximum percentage of seed moisture as compared to other treatments. Furthermore, the regression between temperature of different solar heater boxes and ambient temperature in respect of time and model was also recorded and is shown in Figure 5.

According to the regression analysis, there were no significant differences in temperature or seed moisture over time. There was a linear relationship between the temperature of the solar heater box and the surrounding air, with the significant coefficient of determination (r^2) lying between 0.93 and 0.99. Additionally, it resulted that the seed moisture in a solar heater box without a linear actuator had a strong linear relationship (r^2=0.99) with non-significant effect (P>0.05) regarding time.

With temperature, seed moisture was also found to be influenced with the designed study at different intervals in comparison to seed moisture kept under open sunshine. At beginning, the seed moisture (%) was maximum (almost 60 %) but after 1 hour of solarization it dropped and recorded around 50% (in control condition), whereas the seed moisture recorded in the solar heater box without linear actuator was 45.89±1.56 % and with linear actuator was 39.74±1.97% that shows the exact difference of open solarization and solarization with and without linear actuator. At the end of day, the seed moisture reduced in all treatments, but the reduction of seed moisture was the lowest 12.01±1.82 % in solar heater box with linear actuator and lower 19.14± 3.18 % without linear actuator. The application of linear actuator successfully reduced the maximum percentage of seed moisture as compared to other treatments.

3.2 Data Analysis of Different Solar Heater Boxes using Different Seed Volume

The overall mean temperature and the seed

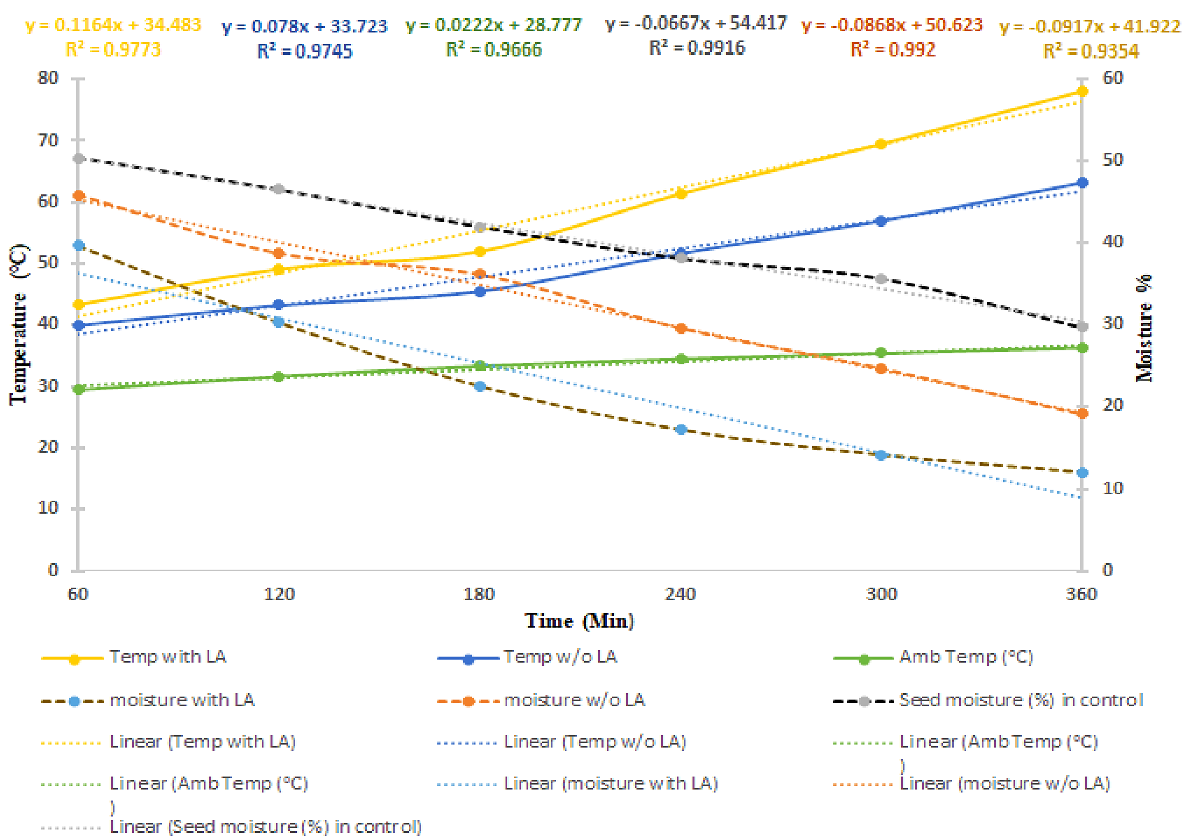


Fig. 5. Regression line showing relationship between temperature and moisture of ambient, with and without linear actuator in solar heater box.

moisture with different quantity of chickpea seeds at different intervals were recorded and are shown in Table 3. These results indicate variability in mean temperature recorded in solar heater box with or without linear actuator for different volume. It statistically ($P<0.05$) effected the penetration of heat between seeds in solar heater box with linear actuator but still it was enough in comparison to the solar heater box without linear actuator and ambient temperature. The temperature was successfully trapped above 60 °C in linear actuator solar heater box with different quantity of seeds (5-40kg). The maximum temperature with minimum volume of seeds was found 76.4±0.99 °C in initial hour of experiment with 5 kg seeds. The increased volume of seeds literally decreased the temperature inside both solar heater boxes. However, the increased volume of seeds inside linear actuator solar heater box at maximum limits of 40 kg still got better results (61.35±0.89 °C) to trap the temperature as compared to the solar heater box without linear actuator (44.95 ±9.6 °C) and ambient temperature (36.33±0.68 °C) at the end of experimental hours (360 minutes).

Overall, these results show that the temperature in linear actuator solar heater box is much better as compared to temperature trapped without linear actuator solar heater box. Similarly, the seed moisture tested in a solar heater box with linear actuator after a period of 6 hours was ideal (11.09±1.26%) for 5kg seed bed (Table 4). Later, it started to increase with the decrease of temperature. The results regarding seed moisture were quite interesting as the volume of seeds was increased it did not allow seed moisture to dry efficiently but still the seed moisture in solar heater box applied with linear actuator produced better results and dried maximum seed moisture 24.74±1.17 % as compared to seed moisture (45.14±1.29 %) without linear actuator at the end of experiment. Meanwhile, the best results came with 5 kg with linear actuator and thus it showed that an application of further powerful motor for linear actuators will work better to get more desired results regarding seed moisture and heat trapping for solar heater box.

The regression estimated that there were significant differences in temperature and seed moisture with respect to seed weight (kg). The temperature in the solar heater box and ambient temperature was linearly related with an essential coefficient of determination (r^2) falling between 0.93 and 0.99. It is also demonstrated that there is not a significantly different ($P<0.05$) but moderate ($r^2=0.67$) linear relationship between seed moisture in solar heater box without linear actuator with respect to the seed weight (kg). Only 67% of the seed moisture variation depended on the weight of seed, according to the moderate coefficient of determination (r^2) value for seed moisture in solar heater box without linear actuator as shown in Figure 6.

In the second experiment, the volume of seeds was increased as to observe the efficiency of linear actuator. The overall mean temperature and the seed moisture with different quantity of chickpea seeds at different intervals were recorded. The results indicated variability in mean temperature recorded

Table 3. Record of temperature in terms of different seed volume with and without linear actuator in solar heater

Seed weight (kg)	Temperature (°C) of solar heater box		Ambient temperature (°C)
	with linear actuator	without linear actuator	
5	76.40±0.99^a	62.69±2.02^b	29.48±0.32^c
10	73.32±1.05^a	59.21±2.71^b	31.65± 0.44^c
15	69.21±1.21^a	56.78±4.65^b	33.32± 0.48^c
22	67.02±1.11^a	53.52±6.49^b	34.48± 0.49^c
30	64.13±1.11^a	49.23±8.62^b	35.40± 0.55^b
40	61.35±0.89^a	44.95±9.60^b	36.33±0.68b

The mean temperatures (Mean ± SE) were separated with least significant difference (LSD) at $p<0.05$ and represented by different letters within the same line.

Table 4. Record of seed moisture in terms of different seed volume with and without linear actuator in solar heater

Seed weight (kg)	Moisture (%) of grains in solar heater box	
	with linear actuator	**without linear actuator**
5	11.09±1.26^{a}	20.89±1.21^{b}
10	15.15±1.01^{b}	35.75±1.97^{b}
15	17.20±1.15 ^{b}	39.18±1.83 ^{b}
22	19.55±1.20 ^{a}	43.64±1.19 ^{b}
30	21.34±1.30 ^{a}	44.73±1.08 ^{b}
40	24.74±1.17 ^{a}	45.14±1.29 ^{b}

The mean moistures (Mean ± SE) were separated with least significant difference (LSD) at p <0.05 and represented by different letters within the same line.

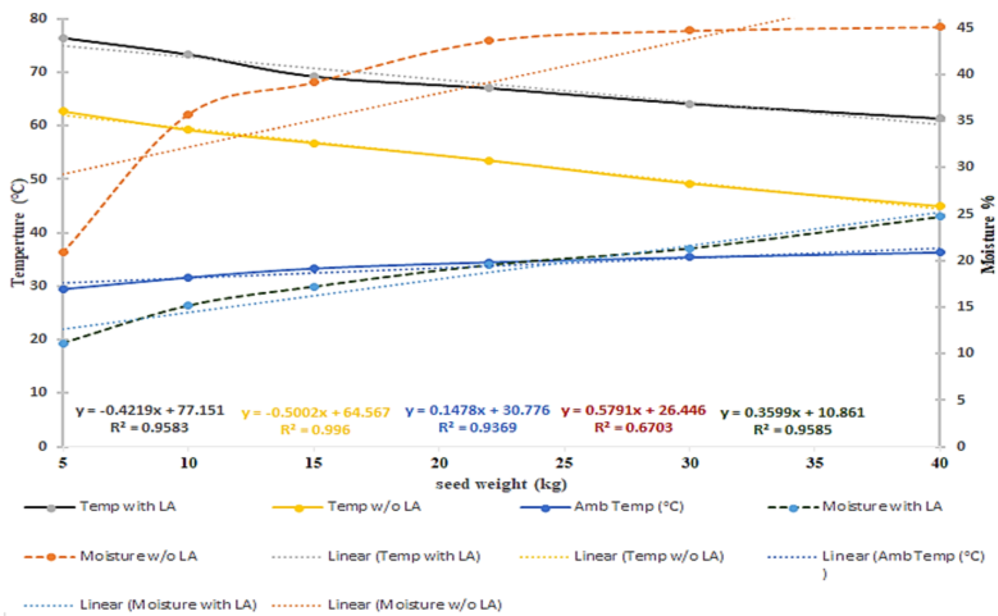


Fig. 6. Regression line showing relationship between temperature and moisture of ambient, with and without linear actuator in solar heater box

in solar heater box with and without linear actuator for different volume. The enough temperature in comparison to the solar heater box without linear actuator and ambient temperature in linear actuator solar heater trapped above 60 °C with different quantity of seeds (5-40kg). The increased volume of seeds literally decreased the temperature inside both solar heater boxes. However, the increased volume of seeds inside linear actuator solar heater box at maximum limits of 40 kg still got better results. Likewise seed moisture was ideal (13.09±1.26%) at 5kg seed at the end of experiment. But the moisture was higher with maximum volume of seed but still the seed moisture in solar heater box applied with linear actuator produced better results and dried maximum seed moisture 24.74±1.17 % as compared to seed moisture (45.14±1.29 %) without linear actuator at the end of experiment. Meanwhile, the best results came with 5 kg with linear actuator and thus it shows that an application of further powerful motor for linear actuators will work better to get more desired results regarding seed moisture and heat trapping for solar heater box. Temperature (>45°C) is the heat lethal zone for most storage pests [23], nevertheless may exist at certain point in the product disinfection system with temperature as high as 50°C [25], unless the heat is maintained for a longer time. The large amount of grain in the solar heating box required longer time to raise the temperature. However, temperature maintenance was maintained for a longer period. A small amount of grain heats up quickly and so as heat losses instantly [16]. The resulting temperature in a solar heater box with linear actuator was suitable for disinfesting the grains from store grain insect pests. Meanwhile, the most studies continue to define 45–50℃ as the lowest effective treatment temperature that must be achieved in a capability or between and in many heat-treated products [22, 23]. Others detailed a temperature range of 50-60°C for product disinfection on preserved arthropods is well enough [26, 27]. The results from previous studies supported the hypothesis that solar heater box is an ideal tool for solarization and can disinfect more products when used for pest control of stored product and further additional application of linear actuator enhanced its efficiency.

4. CONCLUSIONS

An acrylic solar heater box with a linear actuator generated incredibly the highest thermal performance compared to an ambient temperature. The highest mean temperature 61.35°C was found in linear actuator solar heater box which is comparatively the best in performance compared to the solar heater box without linear actuator and an ambient temperature when increasing seed volume up to 40kg in solar heater box. Based on these results, it can be concluded that the solar heater box with a linear actuator is quite safe, cheaper, and environmentally friendly control method that produces enough heat energy to disinfest the store grain pests. Furthermore, the application of linear actuator made the efficiency of solar heater box much better to increase volume of seed inside it. Therefore, such types of solar heater boxes with more powerful motors are recommended in future work.

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6. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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