AGRICULTURAL SCIENCE AND TECHNOLOGY, VOL. 11, No 3, pp 247 - 257, 2019
DOI: 10.15547/ast.2019.03.043

Efficiency of cardboard solar heater boxes for disinfestations of stored grains against arthropod pest

G. Abdullahi[1], R. Muhamad[2]*, O. Dzolkhifli[2], U.R. Sinniah[3]

[1]Department of Crop Protection, School of Agriculture and Agricultural Technology, Modibbo Adama University of Technology, P.M.B. 2076 Yola, Adamawa State, Nigeria
[2]Department of Plant Protection, Faculty of Agriculture, University Putra, 43400 UPM Serdang, Selangor, Malaysia
[3]Department of Crop Science, Faculty of Agriculture, University Putra, 43400 UPM Serdang, Selangor, Malaysia

(Manuscript received 31 March 2019; accepted for publication 17 June 2019)

Abstract. *The solar heater box is a modest technology that enables easy collection and retention of solar radiation as heat at levels lethal to stored product arthropod pest inside the box. This study was designed to construct solar heater boxes of appreciable capacities to hold large quantities of grains, assess their heat-trapping efficiency and the influence of beans quantity and exposure time on same. Solar heater boxes of five different sizes were constructed for this study. Their heat-trapping capacity was evaluated by exposure to the sunlight for 5h. The influence of bean quantity and exposure on heat capture capabilities of the best performing solar heater box was evaluated using five different quantities of cocoa beans (9, 12, 15, 18 and 21kg) for 2h of exposure period. The result for heat trapping capacity shows that the largest solar heater box trapped the highest mean between and within bean temperatures (69.38±4.97 and 69.45±3.97°C, respectively) in 5h of exposure time. The result of the experiment on the effect of bean quantity and exposure time on heat-trapping efficiency show the highest temperature was obtained at 120min exposure time using 9kg of cocoa beans for both between and within bean temperature (70.00±0.73 and 71.23±0.85°C, respectively). The implications of these findings in applying this technology for stored product arthropods pest management on durable commodities were discussed.*

Keywords: cocoa beans, solar heater box, solar heat treatment, pest management

Introduction

Stored products are known to be infested by insect pest, resulting in a substantial loss in quality and quantity annually (Lale, 2002; Hill, 2002; Vargas et al., 2016). Though several methods of pest control have been adopted by farmers and other grain handlers to control insect pests on stored products (Vargas et al., 2016), insecticide is the most commonly used tool (Lale, 2002; Obeng-Ofori, 2008; Kaur et al., 2013). Myriad of problems such as residues in food/feeds, pest resistance, pest resurgence, environmental pollution and poisoning of workers have in recent times made this approach unattractive, which called for the exploration, development and adoption of alternative tools for pest suppression in stored product environment (Vargas et al., 2016).

The use of elevated temperature (above or at 50°C) for the management of stored product arthropod pests through produce and/or structural disinfestation is an ecofriendly stored product protection method (Field et al., 2012). It has been utilised to manage insect pests of stored product for centuries (Fields, 1992; Downes et al., 2008). Solar energy is one of the heat sources through which high temperature can be generated for utilisation in agriculture (Chaikaire et al., 2010) for numerous uses, ranging from produce drying, livestock heating, soil and product heating for disease and pest management (Hansen et al., 2011).

The use of solar heat for the protection of grains from insect pest attack is one of the methods with enormous advantages and offers ample promise for the feature grain storage systems, especially for integration with other methods (Banks, 1998; Bucks et al., 2000). Additionally, the total phase-out of methyl bromide, a famous stored product disinfectant and the reported widespread resistance to phosphine in many species have made the need for the development of credible and rapid alternative phytosanitary protocols for durable stored product; to particularly serve as a quarantine tool at the points of export (Beckett et al., 2007; Subramanyan et al., 2011).

Successful use of solar energy for pest management in stored products requires the use of certain basics tools that will guarantee the application of the required doses of heat without any noticeable effects on product quality (Neven, 2000, 2003). The solar heater box is a handy modest technology that can guarantee easy collection and retention of solar radiation as heat at levels lethal to all stored product arthropod pest inside the box (Ragaa et al., 2013). The use of solar heater boxes made from different materials for the management of stored product insect pests have been demonstrated recently without any effect on moisture content, seed viability and cooking time of the treated product (Mekasha et al., 2006b; Ragaa, 2011; Fawki et al., 2014; Khaled et al., 2015).

Metal constructed solar heater boxes were used by Mekasha et al. (2006) for the management of bruchids on adzuka beans, but the boxes though resilient were found to be too heavy to handle and prohibitively expensive (Ragaa, 2011). The latter author used five different materials for the construction of solar heater boxes and found solar heater boxes con-

*e-mail: rita@upm.edu.my

structured using cardboard paper, painted pure black and glued with aluminium foil from the interior as the most efficient in terms of heat collection and with respect to the cost of production. However, the box size could only handle and efficiently disinfest 7kg of adzuka beans, used as test commodity in that prototype solar heater box. This inspired us to develop cardboard solar heater boxes of bigger capacities that could handle and promptly disinfest larger quantities of grains and to also use another commodity as a test crop. The objectives of this study were to create solar heater boxes with larger grain holding capacity and to assess their heat-trapping efficiency, as well as the effect of both exposure time and quantity of a commodity on their rate of heat collection.

Materials and methods

Design, materials, and construction of solar heater boxes

Solar heater boxes of truncated and inverted pyramid shape were constructed maintaining the obtuse-base- angle of 118° reported to be more efficient in trapping more solar radiation (Mekasha et al., 2006; Ragga, 2011; Fawki et al., 2014) (Figure 1).

Figure 1. Picture and Sketch of the features of the solar heater boxes

Five (5) solar boxes of different size dimensions (Table 1) were constructed and evaluated for their heat trapping capacity. The solar heater boxes were constructed using, cardboard sheets (2mm thickness), polystyrene (12mm thickness), woods (5.08x5.08cm thickness), adhesive glues and nails. The wood served as the frame at each angle and the cardboard was used as walling material for all the lateral sides of the box. The interior sides of cardboard walls were coated with black paint and glued from within with aluminium foil, while polystyrene (12mm thickness) was used as an insulating material from the outside of the cardboard sheets. The adhesive glue and the nails were used joining the components.

Table 1. Dimensions of solar heater boxes used

Components	Boxes/dimension (cm)				
	Standard	1	2	3	4
Top sides (cm)	50	62.5	75	87.5	100
Perpendicular height (cm)	56	70	84	98	112
Base (cm)	30	37.5	45	52.5	60

The cardboard was chosen based on the previous result on its use for the same purpose by Ragaa (2011). The aluminium foil is known to provide a good reflective surface to create long wavelength radiation as reflected radiation argument the sun rays (Aalfs, 2015). The black paint enhanced heat absorbance and retention within the boxes (Ragga, 2011; Fawki et al., 2014). Perforated squared shaped trays made from flat woods were placed at the middle of each box to serve as the platform for keeping the cocoa beans (Ragaa, 2011). The top side of the box was covered with thin transparent plastic films (0.15mm thickness) to generate the needed greenhouse effect inside the box (Aalfs, 2015) and was overlaid by a square wooden frame (Ragga, 2011).

Assessment of heat trapping ability of the different sizes of the solar heater boxes

Experimental design and temperature recording

The experiments for both the assessment of the heat-trapping capacity of solar heater boxes and the effect of beans depths in solar heater boxes on their heat-trapping ability was conducted in a randomized complete block design (RCBD) with four replications. The direction of the sun was used as a blocking factor. The model solar heater box (standard box) used by Ragaa (2011) served as the positive control in the experiment while solar heater boxes 1-4 served as the treatments. Cocoa beans were used as a test stored product commodity.

The trapped temperature in each box type was recorded at 5min intervals throughout the 5h exposure time by a data logger (Intech Micro 2100-16A, Intech Instruments Ltd.) using 'Microscan 2000' software version 4. The pattern of temperature increase in each box was detected using the J-type thermocouples as sensors. Each box at every point in time during the experiment was attached to three thermocouples. All the thermocouples were placed in 1kg cocoa beans in woven fabric kept on the wooden platform at the middle of the solar heater boxes. Two of the thermocouples (5mm diameters) were placed between the cocoa beans lot in the woven fabric bag to capture the between cocoa beans temperature and the other one (1mm diameter) was inserted directly into randomly selected cocoa beans, through a hole drilled into the bean with a hand-held battery-operated Standard PBC drill, using 1mm diameter bit. All readings from the thermocouple were recorded into a personal computer (PC) through the data logger every 5min. Record of temperature at 60min interval was, however, used for statistical analysis and 10 min interval temperature records were used to visualise the trend of temperature increment in each solar heater box.

Assessment of effect of exposure time and quantity of cocoa beans on heat trapping capacity of solar heater box

Solar heater box 4 which was found to trap the highest mean temperature for both between and within bean temperature in the above experiment was used for this experiment. The quantities of cocoa beans were varied according to Makasha et al. (2006a) and Ragga (2011) with slight modifications. The different quantities (9, 12, 15, 18 and 21kg) of cocoa bean were exposed to solar radiation for 2h (between 1200-1500h). The experiment was carried out in RCBD with four replications. Between beans, within bean and ambient temperatures were recorded as described above for the previous experiment and temperature for every 30min of exposure time was used for statistical analysis.

Data analysis

Data for heat-trapping was analysed using a two-way ANOVA using PROC GLM in SAS suitable for RCBD using temperature captured in solar heater boxes after every 60min of exposure time. Temperature recorded at every 10min was used to depict trend of temperature increment in the solar heater boxes over 5h exposures time. Regression analysis was also carried out in SAS using PROC REG procedure to determine the relationship between the recorded temperature in solar heater boxes and the exposure time using the 10min interval temperature readings. Prior to regression analysis, the temperature trend data was log transformed. Data on the effect of bean quantity on the heat-trapping capacity of the best performing solar heater was analysed by two-way ANOVA using PROC GLM procedure for factorial experiment RCBD in SAS. Means for solar heater box heat-trapping capacity were separated using least significant difference (LSD) P=0.05 while Tukey HSD (P=0.05) was used for mean separation in the study on the effect of quantity of cocoa beans and exposure time on temperature accumulation in solar heater box.

Results

Heat trapping ability of the different sizes of the solar heater boxes

Between cocoa beans temperature in solar heater boxes over 5h of exposure time. The result for the mean between cocoa beans temperature trapped in solar heater boxes of different sizes and that of air temperature are shown in Table 2. At 60min exposure time, the results for the mean between beans temperature shows that the size of the box had a highly significant (F= 9.59; DF= 5, 15; P= 0.0003) effect on temperature trapped in the exposed solar heater boxes. As expected, the highest mean temperature of 54.14±5.16°C was recorded in the largest solar heater box (Box 4) but was only significantly higher than the mean between beans temperature of the standard (control) box (40.98±0.80°C) and that of air temperature (30.38±0.56°C), which was in turn significantly lower than mean between beans temperatures recorded in all the solar heater boxes.

Table 2. Cocoa bean temperatures in solar heater boxes for exposure time of 1 to 5h

Box	Exposure time (min)/ Mean±SE trapped temperature (°C)				
	60	120	180	240	300
Air temperature	30.38±0.56^{c}	31.78±1.37^{c}	32.40±0.60^{c}	33.70±1.21^{c}	31.90±1.24^{c}
Standard Box	43.86±0.80^{b}	54.33±1.61^{b}	57.73±1.85^{b}	59.31±1.87^{b}	59.31±1.89^{b}
Box 1	44.16±3.68^{b}	55.58±6.03^{ab}	60.51±1.75^{ab}	63.99±2.68^{ab}	63.78±2.81^{ab}
Box 2	45.56±0.67^{b}	56.68±1.33^{ab}	61.04±1.88^{ab}	66.10±2.50^{ab}	65.38±1.90^{a}
Box 3	48.79±2.42^{ab}	61.16±3.92^{ab}	62.56±2.41^{ab}	69.38±4.74^{a}	66.50±4.73^{a}
Box 4	54.14±5.16^{a}	63.92±3.19^{a}	65.76±5.16^{a}	70.28±5.44^{a}	69.38±4.97^{a}

*Means followed by same letters in the same column are not significantly different p=0.05 (LSD)

At 120 and 180 min of exposure time, ANOVA shows a similar trend of a highly significant (120min F= 13.44, DF= 5, 15, P= <.0001; 180min F= 30.72, DF= 5, 15, P= <.0001) effect of sizes of solar heater box on mean trapped temperatures. The highest mean temperatures of 63.92±3.19°C and 65±5.16°C were recorded in the largest solar heater box (Box 4) at 120 and 180min of exposure period, respectively. These temperature profiles in both cases are only significantly higher than that of the Standard (control) box and air temperature. The differences among the other boxes are also not significant for both exposure times (Table 2).

Mean between bean temperatures recorded at 240min of exposure indicate that for all sizes of solar heater boxes, the control solar heater box recorded the least mean between bean temperatures (59.31±1.87^{0}C). This was, however, only significantly (F= 27.42, DF= 5, 15, P= 0.0001) lower than the mean between bean temperature in box 3 (69.38±4.74°C) and Box 4 (70.28±5.44°C), but was significantly higher than the mean air temperature. The mean air temperature (33.70±1.21°C) was similarly significantly lower than mean between bean temperatures recorded in all solar heater boxes at this exposure time (Table 2).

ANOVA results for the cocoa beans temperatures in solar heater boxes at 300min of exposure show a highly significant (F= 54.28; DF= 5, 15; P= <.0001) effect of the size of solar heater box on their temperature trapping capacity. The highest mean between cocoa beans temperatures of 69.38±4.97°C was recorded in the solar heater box of the biggest (Box 4) but was only significantly different from those recorded in the control solar heater box (59.31±1.89°C) and the mean air temperature (31.90±1.24°C). Similarly, the difference between means between cocoa beans temperatures in box 1 and the control box was not significant (Table 2).

Within cocoa bean temperature recorded in solar heater boxes over 5h of exposure time. The result for mean within cocoa bean temperature recorded in the solar heater boxes over 5h trial time is shown in Table 3. The results for mean within cocoa beans temperature at 60min exposure time reveal that the sizes of the solar heater boxes had a highly significant (F= 6.84; DF= 5, 15; P= 0.0016) influence on their heat trapping capacity. Mean comparison shows that the highest within bean temperature (49.58±2.69°C) was trapped in the largest solar heater box (Box 4). This was, however, only significantly higher than the mean within bean temperature recorded in the standard (control) box (40.98±0.20°C), and the mean air temperature (30.38±0.56°C). Mean within bean temperatures in the control solar heater and other solar heater boxes (except Box 4) did not differ significantly.

Table 3. Effect of size of solar heater box on within seed temperature trapped in solar heater boxes over 5h of exposure time

Box	Exposure Time (min)/ Mean±SE trapped Temperature (°C)				
	60	120	180	240	300
Air temperature	30.38±0.56^{C}	31.78±1.37^{b}	32.40±0.60^{b}	33.70±2.33^{C}	31.90±1.24^{C}
Standard Box	40.98±0.20^{b}	51.05±0.66^{a}	56.90±1.29^{a}	59.53±0.89^{b}	60.80±1.46^{b}
Box 1	47.28±2.38^{ab}	56.10±8.49^{a}	62.00±3.65^{a}	67.88±4.36^{a}	66.90±4.37^{a}
Box 2	48.63±2.59^{ab}	57.15±2.79^{a}	62.30±5.67^{a}	66.95±4.32^{a}	67.15±4.20^{a}
Box 3	48.38±6.84^{ab}	60.30±2.27^{a}	63.60±2.56^{a}	69.23±3.25^{a}	67.35±4.73^{a}
Box 4	49.58±2.69^{a}	62.00±1.52^{a}	64.10±3.07^{a}	68.23±6.07^{a}	67.45±3.97^{a}

*Means followed by same letters in the same column are not significantly different p=0.05 (LSD)

At 120 and 180min of exposure time, no significant difference was found among mean within bean temperature trapped in the solar heater boxes. The mean air temperature (120min; 31.78±1.37°C, and 180min; 32.40±0.60°C) was found to be significantly (120min; F= 8.68; DF= 5, 15; P= 0.0005, 180min; F= 9.06; DF= 5, 15; P= 0.0004) lower than all mean within bean temperatures recorded in all solar heater boxes (Table 3).

At 240min of exposure, the highest mean within bean temperature (68.23±6.07°C) was recorded in solar heater box 4, but was only significantly (F= 31.74: DF= 5, 15; P= < .0001) higher than the mean within cocoa beans temperatures (59.53±0.89°C) recorded in standard (control) box and that of mean ambient temperature (33.70±2.33°C). Differences among mean temperatures of other boxes were not significant (Table 3).

The same trend of mean within bean temperature was trapped in all solar heater box at 300min of exposure time. The highest mean temperature (67.45±3.97°C) was recorded in the largest solar heater box (Box 4) while the least temperature was recorded in the Standard (control) box (60.80±1.46°C). The differences between the mean ambient temperature and the mean within cocoa beans temperature recorded in all solar heater boxes are highly significant (F= 59.69; DF= 2, 15; P= <.0001) (Table 3).

The result for regression analysis for between seed temperature regime in solar heater boxes and that of air temperature is shown in Table 4. The regression estimates indicate that all the solar heater boxes recorded a highly significant (P= <0.0001) linear relationship between temperature regime in the solar heater boxes and exposure time with a significant coefficient of determination (r^2) in the range of 0.8963-0.9694. The linear relationship between exposure time and the ambient temperature is also shown to be significant (P< 0.0001) but had a low coefficient of determination (r^2=0.2485). The low coefficient of determination (r^2) value recorded for ambient temperature indicated only 24.85% of the variation in temperature is dependent on exposure time.

Table 4. Temperature-time regression estimate for between beans temperature trapped in solar heat boxes in 5h exposure period

Solar heater box	Intercept	Slope	r^2	P
Air temperature	1.4597	0.0218	0.2485	<.0001
Standard Box	1.3186	0.1915	0.9694	<.0001
Box 1	1.3396	0.1906	0.9436	<.0001
Box 2	1.4097	0.1677	0.9694	<.0001
Box 3	1.4223	0.1627	0.9631	<.0001
Box 4	1.5550	0.1153	0.8963	<.0001

The regression estimate for within seed temperature is as shown in Table 5. A similar trend of estimates to those shown for between seed temperature is revealed. It is evident from the estimate that there are positive and significant linear relationships between the within seed temperature in the solar heater box and the exposure time. The ambient temperature showed a positive but weaker linear relationship (Table 5).

Table 5. Temperature-time regression estimates for within beans temperature trapped in solar heat boxes in 5h exposure period

Solar heater box	Intercept	Slope	R^2	P
Air temperature	1.4597	0.0218	0.2485	<.0001
Standard Box	1.2184	0.0229	0.9299	<.0001
Box1	1.3121	0.2033	0.9543	<.0001
Box2	1.4676	0.1504	0.9243	<.0001
Box3	1.4276	0.1667	0.9517	<.0001
Box4	1.4777	0.1431	0.8454	<.0001

The trend for between cocoa beans temperature profile in solar heater boxes and ambient temperature is shown in Figure 2. The trend reveals that the highest between beans temperature profile was recorded in Box 4 while the least was in the standard (control) box. It equally revealed that temperature profile for the ambient temperature was relatively stable over the exposure period while those in the treatments and control boxes kept increasing. This trend illustrates that all the designed boxes are relatively better than the control box in temperature trapping. Furthermore, the largest box performed much better than the other boxes in maintaining a much higher temperature regime.

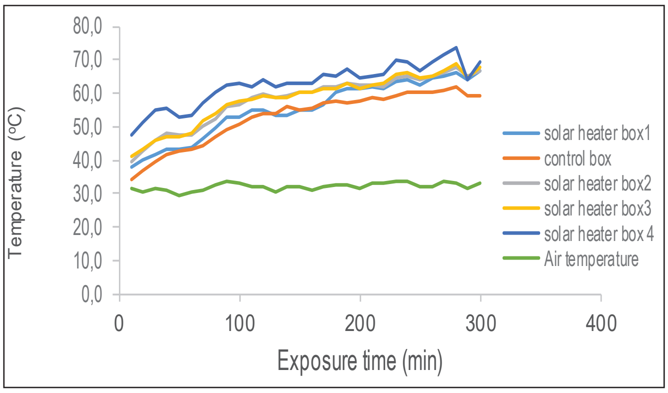

Figure 2. Trend of between beans temperature increases during 5h exposure time

The result of within cocoa beans temperature profile in the heater boxes and the ambient temperature is presented on Figure 3. A trend similar to that of between seed temperature profile (Figure 2) was also observed here. This implies that solar heater boxes will maintain the lethal temperature within the grains contained in them at the time of exposure. This temperature is critical for its cardinal roles for the elimination of all life stages of insects within the treated products.

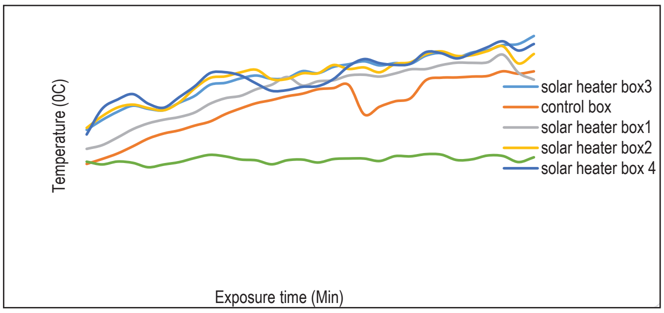

Figure 3. Trend of within temperature increase over 5h of exposure time

Effect of exposure time and quantity of cocoa beans on heat trapping capacity of solar heater box

Main effect for exposure time on heat trapping capacity of solar heater box. The result for the main effect of exposure time on temperature collected in solar heater box is shown in Table 6. The ANOVA for the main effect of exposure on temperature trapped between cocoa beans in solar heater box shows that exposure time had a highly significant (F= 47.49, DF= 3, 60; P< 0.0001) effects on mean temperatures trapped in the solar heater box. Mean comparisons show that the least mean temperature (47.67±1.41°C) was recorded at 30min exposure time and the highest mean temperature (64.03±1.17°C) was recorded at 120min of exposure time (Table 6). The difference among means of trapped between beans temperatures was highly significant (P< 0.0001). Similarly, the highest mean within bean temperature (66.09±1.34°C) was recorded at 120min exposure time and the least (47.89±1.50°C) was recorded at 30min of exposure time (Table 6). Likewise, the difference among means of within bean temperature for all exposure times are highly significant (F= 37.19, DF= 3, 60; P< 0.0001).

Table 6. Main effect of exposure time on heat trapping capacity of solar heater box

Exposure time (min)	Between bean temperature (°C)	Within bean temperature (°C)
30	46.67±1.41^d	47.89±1.50^d
60	54.53±1.08^c	56.61±1.46^c
90	60.72±1.26^b	62.07±1.51^b
120	64.03±1.17^a	66.09±1.34^a

*Means followed by same letters in the same column are not significantly different P=0.05 (LSD)

Main effect for quantity of cocoa beans used on heat trapping capacity of solar heater box. The result for ANOVA for the main effect of the quantities of cocoa beans on mean temperature trapped in solar heater box for between cocoa beans temperature shows that quantity of cocoa beans in solar heater box had a significant (F= 37.17, DF= 3, 60; P< 0.0421) influence on the trapped mean temperatures. The results for the mean comparisons for all tested quantities are presented in Table 7. The result shows that the highest mean between bean temperatures (57.96±2.91°C) was recorded using 9kg cocoa beans in the solar heater box, while the least mean temperature (53.33±1.75°C) was recorded when 21kg of cocoa beans were used in the solar heater box. Furthermore, the result shows that the highest temperature was only significantly higher than the least. On the contrary, the least mean temperature was significantly lower than all the mean temperatures for other quantities except that recorded using 18kg of cocoa beans (Table 7). Similarly, quantities of cocoa beans had a significant (F= 3.61, DF= 4, 60; P= 0.0106) effect on mean within beans temperature recorded for the different quantity of cocoa beans over the 2h exposure time. The least within bean mean temperature (54.51±1.66°C) was equally recorded using 21kg cocoa beans in the solar heater box. This was, however, only significantly lower than those for 9 and 12kg (60.80±1.94°C and 60.55±3.39°C, respectively). Furthermore, the highest mean within bean (temperature (60.80±1.94°C) was recorded using 9 kg of cocoa beans in the solar heater box. This temperature was, however, only significantly (P= 0.0106) higher than those recorded using 18 and 21kg of cocoa beans (56.23±1.42°C and 54.51±1.66°C, respectively).

Table 7. Effect of weight of cocoa beans on mean temperature

Quantity (kg)	Between bean temperature (°C)	Within bean temperature (°C)
9	57.96±2.91[a]	60.80±1.94[a]
12	57.85±1.64[a]	60.55±3.39[a]
15	57.70[a]±2.54	58.74±2.61[ab]
18	56.61±1.59[ab]	56.23±1.42[b]
21	53.33±1.75[b]	54.51±1.66[b]

*Means followed by same letters in the same column are not significantly different P=0.05 (LSD)

Interaction effect of exposure time and quantity of cocoa beans on between cocoa beans temperature.

Result for the effect of interaction between length of exposure time (30, 60, 90 and 120min) and the five different quantities of cocoa beans quantity (9, 12, 15, 18 and 21kg on heat trapped between cocoa beans in solar heater box is shown in Table 8.

Analysis of variance for the combined effect of the different levels of the two factors shows that the interaction effects are significant (F= 1.99, DF= 12, 60; P= 0.0413). To this end, the highest mean between cocoa beans temperature (70.00±0.73°C) was recorded when 9kg of cocoa beans were exposed for 120min, while the least mean between cocoa beans temperature (43.03±1.92°C) was recorded when 21kg of cocoa beans were exposed for 30min. The highest recorded temperature, however, only differed significantly from those recorded for interactions at 30 and 60min of exposure time with all the tested quantities of cocoa beans. Conversely, the least recorded temperature (43.03±1.92°C) was significantly lower than all mean temperatures recorded for all interactions of exposure time of 90 and 120min with all quantities of cocoa beans except the interactions of exposure at 60min using 9kg of cocoa beans. Similarly, interactions with each exposure time had a significant effect on between cocoa beans temperature (Table 8).

Table 8. Interaction of cocoa beans weight and exposure time on beans temperature

Exposure time (min)	Weight (kg)	Mean±SE between beans temperature (°C)	Mean±SE with bean temperature (°C)
30	9	51.54±1.98[cde]	53.15±1.51[cdef]
	12	50.70±2.01[cde]	51.68±1.10[cdef]
	15	44.05±2.67[de]	45.25±1.07[def]
	18	44.04±1.26[de]	44.83±3.09[ef]
	21	43.03±1.92[e]	44.55±2.81[f]
60	9	56.21±4.60[bcd]	57.98±6.18[abcdef]
	12	55.44±0.54[bcde]	57.35±0.36[abcdef]
	15	54.90±2.77[bcde]	56.65±1.38[abcdef]
	18	54.20±1.87[bcde]	55.58±3.20[bcdef]
	21	52.01±1.27[cde]	55.50±1.99[bcdef]
90	9	66.88±1.08[ab]	69.80±3.21[ab]
	12	61.33±1.54[abc]	63.38±2.63[abc]
	15	59.962.52[abc]	62.25±1.55[abc]
	18	58.03±3.89[abc]	57.50±3.17[abcdef]
	21	57.43±2.83[abc]	57.43±2.83[abcdef]
120	9	70.00±0.73[a]	71.23±0.85[a]
	12	65.74±1.12[ab]	69.88±1.63[ab]
	15	65.04±1.54[ab]	69.33±2.10[ab]
	18	59.86±1.01[abc]	60.15±2.58[abcd]
	21	59.53±3.49[abc]	59.86±1.01[abcde]

*Means followed by same letters in the same column are not significantly different P=0.05 (LSD)

Interaction effect of exposure time and quantity of cocoa beans on within cocoa beans temperature.

Results for the effect of interaction between four lengths of exposure time (30, 60, 90 and 120min) and quantities of coca beans (9, 12, 15, 18 and 21kg) on mean within beans temperatures in solar heater box is shown in Table 8. The results show that the highest within bean temperature (71.23±0.85°C) was recorded for interaction of 120min of exposure time and 9kg of cocoa beans.

Correspondingly, the least mean within beans temperature was trapped in solar heater box when 21kg of cocoa beans were exposed for 120min. The highest mean within bean temperature was, however, only significantly higher than those recorded for interactions of 30min exposure times with the whole quantity of beans and those trapped at the interaction of 60min exposure time using 18 and 21kg of cocoa beans. Similarly, the least within beans temperature was also only significantly lower than those obtained for the interaction of 90min exposure times with 9, 12 and 15kg of cocoa beans as well as all interaction at 120min for all tested quantities of cocoa beans (Table 8).

Discussion

Solar heater box is a technology that collects solar radiation in a target environment for thermal control of stored product pests at a preset exposure period that is believed to be judicious to guarantee product disinfestation with absolute assurance on product quality (Mekasha et al., 2006; Ragaa et al., 2013). The present study used solar heater boxes of five different sizes to assess their potentials to trap reasonable solar radiation that can be harnessed for insect pest control on stored durable commodities. The target of using solar collectors in solar energy thermal sequestration is to facilitate concentration of as many photons of solar radiation of any wavelength at the spot of interest to achieve a targeted temperature range (Rudriguez et al., 2004). Solar energy collection for optimal utilisation for agricultural purposes in general and pest control in particular demands that some modest facility needs to be purposefully put in place (Kalogirou, 2004). For maximum efficiency, the collector chosen must be made of materials with basic characteristics such as high reflectance of ultraviolet radiation of not less than 92% (Rodriguez et al., 2004). The ideal material for thermal collectors also needs to be cheap, preferably durable under prevailing weather conditions in its target use environment and of extreme reflectance within the expected UV range (Kutscher et al., 1994). Additionally, it must be resistant to the destructive tendencies of the UV (Rodriguez et al., 2004). Other desirable qualities are high heat absorbance and low thermal emissivity (USDE, 2002; Aalfs, 2015) so as to be able to retain most of the trapped heat. Lastly, careful choice of materials and design of solar collectors can improve their performance under practical applications (Kalogirou, 2004). The design used for the heater boxes used in this study was based on reports of its proven abilities reported in the literature by some workers (Mekasha et al., 2006; Ragaa, 2011; Ragaa et al., 2013; Fawki et al., 2014 and Khaled et al., 2015).

Results for heat trapping capacity of solar heater boxes of different sizes used in this study show that the largest box trapped the highest both between and within beans temperatures which ranged from 54 to 70.28°C and 49.58 to 68.23°C, respectively. These temperature regimes are within the thermal lethal zone (>45°C) for most stored product pests (Beckett et al., 2007), even though some survival is possible at some point in product disinfestation system with temperature <50°C (Beckett et al., 2007; Beckett, 2011) unless the heat is retained for a very long time. Nevertheless, most studies still set 45-50°C as the minimum effective treatment temperature that must be attained in a facility or between and within the bulk of the commodities being thermally treated (Field, 1992; Neven, 2000; Beckett et al., 2007; Beckett, 2011). Others like, Imholte and Imholte-Tauscher (1999); Mahroof et al. (2003) and Dosland et al. (2006) independently set the target temperature of 50-60°C for product disinfestation from stored product arthropods. The above citations strengthen our belief that the largest solar heater box, which has captured the highest mean temperature may disinfest more quantities of a commodity when purposefully applied in stored product pest management.

Furthermore, having been made from materials that are cheap and readily available makes it a technology of choice that can enable resource-poor farmers to take advantage of the surplus benefits that the use of solar energy offers in our contemporary moment; in response to global quest on use of safer phytosanitation methods devoid of the unwanted drawbacks of synthetic pesticides on agricultural products (Neven, 2003; Subramanyan et al., 2011; Ragaa et al., 2013). The merit of using solar energy relative to other kinds of energy lies in it being clean, green, renewable and the fact that it can be harnessed with no associated environment problem accompanied with others (Kalogirou, 2004). It is free and readily available especially in tropical and subtropical environments (Mekasha et al., 2006; Ragaa et al., 2013) and can be used with insignificant consequences on product quality (Subramanyan et al., 2011). It is, however, pertinent to note that enormous disparities exist among both species and commodities with respect to their thermal intolerance and tolerance, respectively, during heat treatments (Beckett et al., 2007).

Therefore, the target in the use of any device in thermal disinfestation is to apply heat onto the commodity at such level that will strike a delicate balance between these contrasting scenarios at a confluence zone, Neven (2003) referred to as 'zone of opportunity'. This is a point of intersection between the two extreme phenomena where maximum thermal mortality is experienced in the pest population with negligible effect on commodity quality. Similarly, differences of heat intolerance within species life stages have also been reported (Arthur, 2006). Each life stage of every species must, therefore, be tested to establish its specific lethal temperature zones to be able to take full advantage of control potential offered by the use of this solar heater box. This will cater for the difference in the innate ability of species and their life stages to succumb to elevated heat to be accommodated (Beckett et al., 2007).

The result for the regression analysis produced a high coefficient of determination and positive estimates for between and within bean temperature, respectively. This implies that the linear positive relationship exists between temperature accumulation in solar heater box and exposure time. The low coefficient of determination (r^2= 0.2485) obtained for ambient temperature indicates that only 24.85% of ambient temperature at any point in time during the experiment will be due to the length of exposure time. It further implies that changes in exposure time caused little changes in ambient temperature as compared to over 89.66% in the largest solar heater box. This further strengthens the declaration on the ability of the solar heater boxes of not only being able to retain more heat within it compared to what is obtained in the environment surrounding them, but also of the influence of exposure time on such collected heat. These findings are in accords with those of Mekasha et al. (2006) and Ragaa (2011).

The result for the trend of temperature increment in solar heater boxes and the ambient environment indicate that all the solar heater boxes used are efficient in heat-trapping. This is because the temperature profile recorded in the solar heater kept increasing with exposure time relative to the ambient temperature that has shown to have remained relatively stable for both the between and within bean temperature. The efficiency of any solar heater collector is underpinned by its capability to hold incoming solar radiation and its subsequent conversion to heat energy and at the same time retaining the thermal energy at the desired location with negligible losses (Kalogirou, 2004).

A critical look at the thermal increment trend lines for both between and within bean temperature will show that in spite of the ambient temperature remaining low (29-33^{o}C), temperature profiles in the solar heater boxes rose to points in the range of 50-79^{o}C in the largest solar heater box. This finding is in accord with those reported in similar earlier independent studies using solar heater boxes by Mekasha et al. (2006) and Ragaa (2011). The trend of temperature profile in solar heater boxes can be attributed to combined effect of high heat absorption capacity of black paint, good reflectance property of aluminum foil, low conductivity of cardboard paper and high glazing ability of thin plastic films used in the construction of the boxes (Rudriguez et al., 2004; Mekasha, 2004; Ragga, 2011).

The result for the main effect of exposure time on both between and within bean temperature trapped in solar heater box over the two hours exposure time used in this experiments clearly show that the higher the exposure time, the higher the temperature collected. This means that solar heaters need to be exposed to the solar radiation for 60 to 120min. This is because the mean temperature captured for 30min (46.67^{o}C and 47.89^{o}C between beans and within bean, respectively) was short of the effective insecticidal temperature (>50^{o}C) requirement for the disinfestation of durables from insect pest infestation (Fields, 1992) though death may occur at such levels only when maintained for 24h (Fields, 2006). The result further suggests higher temperatures are trapped within the bean than those between the beans, suggesting that even individuals embedded within the bean can receive lethal temperatures that can eliminate them economically. The thermal dose in heat treatment has been reported to be the combined effects of temperature and exposure time (Qaisarani and Banks, 2000; Ma and Ma, 2012). To guarantee proper disinfestation using this technique, exposure time must be given due considerations and should be set at levels quite assuring for adequate heat entrapment within the solar heater box.

The result for the main effect of quantity of beans (Table 7) on temperature capture in solar heater box suggests that an inverse relationship exists between the quantities of beans and mean temperature captured between and within cocoa beans. The highest temperature (57.96±2.91 and 60.80±1.94^{o}C) for between and within seed was captured with the inclusion of 9kg of cocoa beans in the solar box and the least (between beans 53.33b±1.75^{o}C and within beans 54.51±1.66^{o}C) was recorded when 21kg of cocoa beans were used in the solar heater box. Additionally, the results show the plausibility of disinfesting up to 21kg of cocoa beans using a solar heater box of this capacity since mean temperatures recorded for both within seed and between seeds are within the levels the stored product insect pest cannot tolerate due to cessations of many biochemical and physiological processes vital for insect survival (Neven, 2000). The effect of seed quantity (determined by seed depth) on the rate of temperature accumulation in solar heater box has been known for decades. Yoshida and Girchuku (1983) while investigating the effect of solar heat for control of insect pests found that thin seed depth accumulated heat faster but equally lost it rapidly. They also found that higher seed depth retards the rate of both temperature accumulation and loss in stored durables. They recommended that higher exposure time will be needed if the quantity of the commodity to be thermally disinfested is much.

The result for the interaction effect of cocoa beans quantity and exposure time on heat accumulation in solar heater box show significant (P= 0.0413) interaction exists among levels of the two factors used in this study. The highest exposure time (120min) using the least tested quantity of cocoa beans (9kg) gave the highest mean temperature (between beans 70.00±0.73^{o}C and 71.22±0.85^{o}C). On the other hand, the least mean temperature was obtained when 21kg of cocoa beans were exposed for 30min (Tables 8 and 9). The amount of commodity mass is known to influence heat accumulation in solar heaters (Aalfs, 2015). This result implies that the higher the number of cocoa beans to disinfest, the higher the exposure time that may be required and vice versa. This point is important because the possibility of injury and eventual death is higher with an increase in thermal dose of more elevated temperature (Yocum and Denlinger, 1993). Therefore, increase the exposure time with an increase in cocoa beans depth will ensure that thermal dose is achieved in all parts of the bulk lot. The need to do lies in the fact that the overall effect of elevated temperature on target individuals is influenced by milieu (the exact location of the insect in the lot and the condition of the commodity around the individual), rate of heating of the product by the method being used, the attainment of desired temperature, and the length of heating time, (Neven, 2003; Subramanyan et al., 2011; Al-Amri, 2013). Thermotaxis, a situation where insect migrates to cooler points in response to increasing temperature profile above their physiological optimum during heat disinfestation, is common with stored product insect pest (Beckett et al., 2007).

Cocoa beans was used as candidate stored product in this study because it is one of the major durables in international trade. It is also known to contain some appreciable amount of some dietary nutrients (like protein, fats, carbohydrates, moisture), non-dietary constituents (fibre) and some mineral elements (Anvoh et al., 2009; Afoekwa et al., 2013). These constituents are the core determinants of the nutritional values of the products manufactured from cocoa beans (Joel et al., 2014; Tettey et al., 2015). Insect pest infestation of cocoa beans is known to cause deterioration in the quality and quantity of cocoa beans (Dharmaputra et al., 1999; Jonfia-Essien et al., 2010) with detrimental consequences on food and market value (Jonfiah et al., 2010; Tettey et al., 2015). This normally calls for adoptions of control measure in form of curative or prophylactic intervention using a toxic chemical (Asimah et al., 2014). Any technique developed as an alternative to synthetic insecticides to control insect pest on stored product including cocoa beans must provide safety assurances against the amount and proportions of the chemical and mineral constituent of the treated product.

Conclusion

It could be concluded from the result of this study that: a) the size of solar heater box significantly affects its heat-trapping capacity; the solar heater with the largest capacity trapped the highest mean temperatures of 69.38±4.97 and 69.45±3.97°C in 5h for between and within cocoa beans, respectively, and the temperatures are at levels lethal to arthropod pests of stored products; it also gave the steepest slope after regression analysis of 0.1953 and 0.2431 (between and within bean, respectively); b) both exposure time and quantity of cocoa beans had a significant influence on the rate and extent of heat accumulation in the solar heater box and that the interaction of both factors also significantly affects the heat trapping capacity of solar heater boxes; exposure at 30min using 21kg of cocoa beans gave the least mean temperature for both between and within bean temperature (43.03±1.92 and 44.83±3.09°C, respectively), while the highest temperature was obtained at 120min exposure time using 9kg of cocoa beans for both between and within cocoa beans temperature (70.00±0.73 and 71.23±0.85°C, respectively); the higher the quantities of beans to be disinsected at a time, the higher should be the exposure time and vice versa. This study has, therefore, provided an insight into the better potential of cardboard solar heater boxes of larger sizes in trapping more solar heat at regimes lethal to arthropod pests of stored product, and on the effect of exposure time and quantity of a commodity, and their associated interaction on the same. Lastly, it is good to state that this technology will be affordable to even resource-poor farmers who hardly afford the cost of synthetic insecticides and their associated application equipment, as it was made from cheap materials that can be easily obtained in most farming communities.

Conflict of Interests

No any conflict of interests.

Acknowledgments

We gratefully acknowledge all the useful comments from those who read the manuscript, for indeed all suggestions were helpful in improving the paper. The first author wishes to also thank the management of Modibbo Adama University of Technology, Yola, for supporting the funding of his study under the AST&D scheme of TETfund - Nigeria.

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