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Effectiveness of the solar biomass hybrid dryer for drying and disinfestation of maize

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ABSTRACT

The Solar Biomass Hybrid Dryer (SBHD) is a new technology developed in Ghana for grain drying and utilizes biomass (agro-residues, timber scraps, etc.) along with solar drying, and is especially useful for drying during rainy periods of the year when solar drying cannot be relied on. This study assessed the effectiveness of a 5.0-MT SBHD comprising a solar tent and a furnace for thermal drying and disinfestation of maize. Mortalities of adults of *Sitophilus zeamais* (Motschulsky), *Tribolium castaneum* (Herbst) and *Cryptolestes ferrugineus* Stephens were assessed. Additionally, mortalities of immatures of these three species were assessed. Internal and cage temperatures (°C) in the SBHD, sun drying (SD) and laboratory (control) were monitored, as were moisture content (MC) and thermally (stress) damaged kernels (TDK) (%). During the 7-h experiment, mean internal temperatures in the SBHD, SD and laboratory were 52.3 ± 1.0 °C, 41.4 ± 0.8 °C and 30.3 ± 0.2 °C, respectively. Similarly, temperatures in cages in the SBHD (49.5 ± 1.0 °C) were higher than those for cages in the laboratory (29.9 ± 0.2 °C) and SD (38.2 ± 0.6 °C). Reduction in the moisture content of maize dried using SBHD, SD and under laboratory conditions were 7.7, 5.2 and 2.9%, respectively. This corresponded to grain MC reduction rates of 1.1%, 0.74% and 0.4% per hour. There was 100% mortality of *S. zeamais* and *C. ferrugineus* adults achieved in only the SBHD; some immatures of all three species survived in all three treatments. However, survival of immatures was highest in the laboratory, followed by SD and lowest in the SBHD for all three species. Percent TDK was higher in the SBHD (6.7 ± 0.9) than SD (3.3 ± 0.3) and laboratory (2.7 ± 0.3). These data show that the SBHD is effective for both drying and disinfestation of grain.

1. Introduction

Maize (*Zea mays* L.) is the third most important cereal grain worldwide after wheat and rice (Golob et al., 2004; Suleiman et al., 2013). In developing countries, maize provides substantial amounts of calories, proteins and minerals to millions of people (FAO, 2011; Mwololo et al., 2013). In countries with tropical and subtropical climatic conditions such as Ghana, a large proportion of maize is harvested with moisture content ranging from 18.7 to 26.8% (Alliance for a Green Revolution in Africa (AGRA), 2013) and stored under warm and humid conditions (Hell et al., 2008). Most farmers lack knowledge of the importance of storing maize under ideal conditions. In addition, farmers have limited access to efficient drying equipment. This is especially important when harvesting occurs under unfavorable weather conditions such as during the rainy season (Weinberg et al., 2008; Tefera, 2012). High grain moisture content and temperature influence rapid deterioration and stimulation of growth and development of insect pests and fungal infections (Alborch et al., 2011; Hell and Mutegi, 2011; Suleiman, 2015). Extending field drying to reduce grain moisture content could result in serious grain losses during storage because such a practice enhances infestation of grain by storage insect pests and promotes toxigenic field fungal infection (Kaaya et al., 2006; Baidoo et al., 2010); it also increases pre-harvest losses, for example, ears that drop from the plant, broken stems, bird damage etc. Post-harvest preservation of maize through reducing grain

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moisture content to prevent fungi development and controlling insect pests is essential for long term storage to enhance food and feed security.

Insecticides are the method of choice for insect pest control among most smallholder farmers throughout most of the developing world because they are relatively affordable and usually effective (Hell and Mutegi, 2011). Nonetheless, chemical disinfestation has drawbacks such as the development of resistance, concerns about worker safety, consumer concerns regarding chemical residues in food, and other environmental-related concerns (Vadivambal et al., 2010). Indiscriminate use of phosphine by farmers has resulted in human deaths, development of resistance in insects and control failures (Sayaboc et al., 1998).

Challenges in storage pest management have spurred the search for non-chemical alternative management strategies; those that are affordable and ecologically viable. According to Hodges (2012) and Nsafoah (2012), small-scale farmers in Africa rely on sun drying to dry maize and other crops prior to storage. Usually, sun drying takes time to reduce grain moisture content to safe moisture levels and it cannot heat the grain uniformly and efficiently to achieve lethal effect on insects (United States Department of State (USDS), 2013). Trapping solar energy for drying and disinfestation of grains is considered a better option to sun drying. Solar energy has been used for direct disinfestation of grain for thousands of years (Beckett et al., 2007). For example, in China, grain was heated in a thin layer to >50 °C and <12% MC and then piled up to maintain the high temperature for several hours before storage in insulated bins (Liu et al., 2003). Heat treatment is pervasive, relatively rapid and residue-free (Beckett and Morton, 2003), and can achieve complete mortality, and results in pesticide-free products (Beckett et al., 2007).

The effects of solar heating on *Callosobruchus* spp. (Coleoptera: Chrysomelidae) have been investigated (Chauhan and Ghaffar, 2002; Lale and Vidal, 2003; Fawki et al., 2014). According to Chauhan and Ghaffar (2002), solar heating seeds of pigeonpea (*Cajanus cajan* (L.) in transparent polyethylene bags effectively controlled damage caused by Bruchids (*Callosobruchus* spp.), with no reduction in seed germination. The temperature in seed bags was raised to 65 °C by solar heating and heat-treated seeds remained free from bruchid damage for at least 41 wk of storage (Chauhan and Ghaffar, 2002). The effects of simulated solar heat on oviposition, development and survival of *Callosobruchus maculatus* (F.) and *Callosobruchus subinnotatus* (Pic) in stored Bambara groundnut, *Vigna subterranea* (L.) Verdcourt, at three high temperatures (40°, 45° and 50 °C) at a constant, low humidity (30% relative humidity) have been studied (Lale and Vidal, 2003). According to Lale and Vidal (2003), exposure of *C. maculatus* eggs to 50 °C for 6 h or *C. subinnotatus* eggs to the same temperature for 2 h results in no adults developing from eggs. Fawki et al. (2014) investigated the effects of solar energy on *C. maculatus* (F.) infesting cowpea seeds (*Vigna unguiculata* (L.) using a metal-box heater. They showed that the box heater attained 54 °C and resulted in 100% of adult beetle mortality within 15 min, and totally suppressed the beetle population when immature stages were exposed to the solar energy for 20 min at 58–64 °C.

Kwame Nkrumah University of Science and Technology (KNUST) in Kumasi, Ghana, has developed the solar biomass hybrid dryer (SBHD) (Akowuah et al., 2018). The hybrid dryer utilizes biomass (agro-residues, timber scraps, etc.) along with solar drying. The hybrid dryers reduce drying times by maintaining high temperature and low humidity, resulting in a faster drying rate than solar drying alone. These dryers are being scaled-up, targeting nucleus farmer aggregators, farmer-based organizations, poultry farmers, post-harvest service providers, seed companies and other stakeholders in the maize value chain in Ghana. The fact that the SBHD utilizes biomass along with solar drying means these dryers have a high potential for effective grain disinfestation. Therefore, in this study, the performance of a 5-MT SBHD that integrates both solar and biomass energy for maize drying in commercial quantities was investigated for its ability to dry and disinfest maize of stored grain insect pests.

2. Materials and methods

2.1. Solar biomass hybrid dryer

The SBHD (7 m × 6 m x 3 m) used to conduct this experiment in March of 2018 is located at Agona-Jamasi in the Ashanti Region of Ghana, with geographical coordinates of 6° 44′ 0″ North, 1° 32′ 0″ West. This 5.0-MT SBHD consists of a solar tent and a furnace. The SBHD tent was constructed using fiberglass that was laid over a wooden frame. The dryer has six levels of shelves where grain is spread to ensure uniform drying. The SBHD used in this study is similar to one described in Akowuah et al. (2018). In this experiment, *Trichilia monodelpha* wood, purchased from the main Agona-Jamasi market, was combusted in the furnace to generate heat to feed into a conveying pipe that connects to the solar tent. A total of ~100 kg of logs with a cost of US$42.00 was combusted during the experiment. However, the intended feedstock for the SBHD is agricultural waste such as maize cobs and husks which can be combusted instead of wood to generate heat and significantly reduce cost. The furnace is a useful component of the dryer especially for drying during cloudy and/or rainy days. Sun drying (SD) involved spreading maize out to dry on tarpaulin. During the day of the experiment, ambient temperatures were above 24 °C for a minimum of 6 h.

2.2. Maize

Maize variety “Obatanpa” with a moisture content (MC) of ~13.2% was obtained from a farmer at Ejura in the Middle Belt of Ghana and transported to the experimental site. The initial MC was determined using the PHL-IL moisture meter developed by USDA-ARS in Manhattan, KS, USA (Armstrong et al., 2017) and a John Deere (JD) moisture meter manufactured by agraTronix™ (Moisture Check Plus™, SW08120, Illinois, USA). The grain was then preconditioned to 20.3% MC and 27.4 °C — measured with John Deere moisture meter — by adding ~45.4 L of distilled water to 0.5 MT of maize (Rahman et al., 2011). The 20.3% MC level was used because most of the maize in Ghana at harvest has 18.0–26.8% MC. To ensure uniform moisture distribution, the grain was covered with tarpaulin (polypropylene based) for a 24-h period prior to the experiment.

2.3. Insects

2.3.1. Laboratory insect cultures

Adults of *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae), *Tribolium castaneum* Herbst (Coleoptera: Tenebrionidae), and *Cryptolestes ferrugineus* Stephens (Coleoptera: Laemophloeidae) were obtained from stock cultures maintained in the Entomology Laboratory of the Department of Crop and Soil Sciences of Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana. *Sitophilus zeamais* is an internal feeding species and was cultured on insect-free whole maize kernels obtained from Ejura whereas *T. castaneum* and *C. ferrugineus*, are external feeding species and were cultured on cracked maize to provide insects with enough nourishment.

2.3.2. Adult insects for mortality assessment

One-L Kilner jars containing 600 g of maize were used. Three jars were set up for each of the three species and 50 unsexed adults of the respective species were introduced into the jars, i.e. nine jars for the three species. The Kilner jars were then covered with muslin held in place with rubber bands to ensure air exchange. The adult insects of each species added were left in the jars for 10 d to oviposit, and the oviposition conditions were 30 ± 1 °C and 65 ± 5% r.h. After 10 d, all the adults were sifted out of the jars using U.S.A. Standard Sieve Series with mesh sizes between 0.71 and 2.0 mm (Dual Manufacturing Co., Franklin Park, IL, US). The rearing media were put back into their respective jars and maintained in the laboratory at 30 ± 1 °C and 65 ± 5% r.h. for 3–4 wk, depending on the species, to assess emergence of F_1 progeny. Rearing procedures continued until F_2 adult emergence. Egg collection, rearing conditions and diets are similar to those described above. Therefore, there were nine new culture jars with F_2 adults, with three culture jars containing insects for each species. Emergence of F_2 progeny was monitored daily for 2–3 wk and those emerged adults transferred to fresh diets of the respective species in new jars, making sure the F_2 adults from the different jars were kept separate. These F_2 individuals were used for the experiment.

2.3.3. Immature insects for mortality assessment

Nine 5-kg portions of maize were set up in 15-L plastic containers. For *T. castaneum* and *C. ferrugineus*, 2.5-kg of each 5-kg portion was cracked to provide insects with enough nourishment. Three 5-kg portions of maize out of the nine were infested with 200 unsexed adult insects of mixed age of each of the three species tested. Adults used for infestation of the 5-kg portions of maize were from the laboratory cultures. Adults were left to oviposit in the 5-kg portions of maize for 21 d at 30 ± 1 °C and 65 ± 5% r.h. The 15-L containers with insects were each covered with muslin held in place with rubber bands to ensure good exchange of air. After the 21 d, all adult insects in each of the 5-kg portions of maize were sieved out hence only immatures were used for the experiment. After sieving out adults, three 500-g portions of maize were then weighed out of each 5-kg portion of maize for the experiment, i.e. twenty-seven 500-g portions of maize were used for the three species.

2.4. Experimental treatments

The two drying methods, SBHD and SD, served as two of the treatments. Maize kept under laboratory conditions served as the control. The MC of maize in each of the three treatments was monitored during the experiment and final readings noted after 7 h of the experiment. Treatments and controls were replicated three times for each of the species.

The insects in these replications were kept in wire mesh cages that were exposed to conditions in the SBHD, SD, or laboratory for the duration of the experiment. To test mortality of immatures, insects in 500-g portions of maize in each treatment were spread out separately to a depth of 1.3 cm on drying trays in the SBHD, tarpaulin in SD, or on top of a bench in the laboratory.

2.5. Cages for assessing mortality of adult insects

Twenty-seven cube-shaped wire mesh cages (12 cm × 12 cm x 12 cm) fabricated from fine wire mesh (McNichols® quality wire mesh, square weave, copper alloy, woven construction, 40 mesh, 0.25 mm wire, 0.38 mm opening, 36% open area, coil: McNichols Co. Tampa, FL, USA) were used for the experiment. Each of the 27 wire mesh cages was filled with 180 g of conditioned maize grains to a depth of 1.3 cm. Nine cages were assigned to each insect species. Twenty live adults (F_2) of *S. zeamais*, *T. castaneum* and *C. ferrugineus* were accordingly introduced into each of the 27 wire mesh cages containing 180 g maize.

The wire mesh cages containing insect species were carefully sealed along the edges with masking tape to prevent escape of insects. Apart from the 27 wire mesh cages with insects, there were nine cages which contained only 180 g of maize to a depth of 1.3 cm, but these contained no insects. Tinytag® loggers (Gemini data loggers, Chichester, West Sussex, UK) were placed in each of the nine wire mesh cages to continuously monitor temperature and r.h. inside the cages throughout the experiment. Three of such cages were placed randomly inside the SBHD, three in the SD and the rest (three) in the laboratory to monitor temperature and r.h. inside the cages. Besides being placed in cages, Tinytag loggers were also set up inside the SBHD, in the SD arena and laboratory to monitor temperature and r.h. in these locations.

The wire mesh cages were randomly distributed on the drying beds of the SBHD and on the tarpaulin (in SD) after the maize had been spread out to dry. The top-most drying bed of the SBHD was divided evenly to nine sections and each section was randomly assigned one of the nine wire mesh cages (three cages each for *S. zeamais*, *T. castaneum*, and *C. ferrugineus*). The distribution of the nine cages on the tarpaulin was conducted in a manner similar to what is described for the SBHD above. The nine cages in the laboratory were randomly distributed on top of a laboratory bench. Temperature and r.h. in cages were monitored as previously described.

After the 7-h experiment, the wire mesh cages were removed and taken to the Entomology Laboratory at KNUST for processing. Insect mortality was determined 24 h after the experiment by counting numbers of dead and live insects after sifting the grains using the USA standard sieve series described previously. “Dead” insects had no movement when prodded.

2.6. Portions of 500 g of maize for assessing mortality of immature insects

The twenty-seven 500-g portions of maize referred to earlier were used for the experiment. To ensure replication of each species, three 500-g portions of maize were taken from each 5-kg portion associated with each species and were randomly assigned to the SBHD, SD, or laboratory treatments. This means that there were nine 500-g portions each in the SBHD, SD, and laboratory treatments — three 500-g portions in each treatment were for one insect species, i.e. three replications.

After the study, nine 500-g portions of maize that went to either the laboratory, SD, or SBHD were put in respective Kilner jars and incubated at 30 ± 1 °C and 65 ± 5% r.h. Additionally, three 500-g portions of pre-conditioned maize taken before the experiment, three 500-g portions taken from SBHD after the experiment, and another three 500-g portions from the SD treatment that were taken after the experiment were also incubated together with the twenty-seven 500-g portions referred to earlier. Therefore, a total of 36 Kilner jars were kept for 60 d after the 7-h experiment. The Kilner jars were covered with muslin cloth fastened with rubber bands and were kept in the laboratory under conditions previously stated for 60 days. Maize was sifted at 40, 47, 54 and 60 days after the experiment in order to count the number of live and dead adults that emerged from each jar.

For the nine 500-g portions taken before the experiment (preconditioned maize), it involved taking small portions from different parts of all the preconditioned maize to add up to 5 kg, mixing thoroughly and weighing out three 500-g portions from this 5 kg using a dial spring scale (SP, CAMRY, Yongkang, PRC). In the case of the SBHD, it involved taking small portions of maize from different

parts of the drying beds to make up 5 kg, mixing them thoroughly and weighing out three 500-g portions. In sun drying, the three 500-g portions were obtained in a manner similar to that for the SBHD except the small portions were taken from maize drying on tarpaulin.

2.7. Experimental set up

The experiment was conducted on a day when ambient temperatures were above 24 °C for a minimum of 6 h. Assessment of the three treatments was conducted concurrently. Maize of the same initial MC of 20.3% was used for all the treatments. The SBHD had six vertical levels of drying trays/drying beds, each with a wire mesh base to hold maize being dried. However, only the top-most platform was used for the experiment because it was expected to receive the highest amount of solar radiation and was expected to be similar to the amount received by the SD treatment. The top drying beds had sixteen compartments. Approximately 260 kg of preconditioned maize was evenly spread on the top shelves by spreading 20 kg on 13 out of the 16 compartments, to a depth of 1.3 cm, leaving three compartments where the 500-g maize portions containing immatures of three species were also spread to a depth of 1.3 cm. In the sun (SD), 100 kg of maize was spread on a tarpaulin to the same depth of 1.3 cm as had been done in the dryer. Nine 500-g maize portions containing immatures of the three different insect species were also spread on tarpaulin used in the SD treatment. In the laboratory, the same procedure was repeated i.e. nine 500-g maize portions containing immatures of the three different insect species were spread on top of a laboratory bench.

Based on the information provided above, the experimental design for this study was a Completely Randomized Design (CRD) with three replications. Response variables were mortality of adults in cages, mortality of immatures in 500-g maize portions (number of adults counted after 60 d of incubation), number of thermally cracked kernels, MC of maize (maize drying rate), temperature and r.h in the SBHD, SD and laboratory.

2.8. Determination of maize moisture content

The MC was recorded continuously at hourly time intervals as the grain was being dried using the John Deere meter. Moisture content determination was done by collecting maize samples from five different parts of the drying beds, tarpaulin, or laboratory bench top, thoroughly mixing them and taking the MC reading. At each time, three measurements were taken, and the means calculated. Recording of MC was continuous until the 7-h experiment ended. Additionally, maize grain temperature was taken along with the MC using the John Deere meter.

2.9. Thermal kernel cracking

Samples of the pre-conditioned maize were taken before the experiment and after drying, in the three treatments, to determine stress- or thermally-cracked kernels. One hundred maize kernels of each treatment were randomly selected and examined using a stereo microscope. Damaged (heat-cracked) kernels per 100 grains were counted. A kernel was considered to be thermally cracked if it had one or more cracks along the seed-coat (Akowuah et al., 2018). There were three replications for each treatment.

2.10. Data analysis

Analysis of variance (ANOVA) methods were used with SAS Version 9.4 (PROC MIXED; SAS Institute, Cary, NC). A two-factor factorial arrangement (factors were species and drying method) was utilized in a CRD. The simple effects of drying method given species and species given drying method were assessed with a SLICE option in an LSMEANS statement. Statistical differences were determined to be p-values less than 0.05. The SLICE option is the classic analysis of simple effects, which is appropriate given the significant interactions that were found. Percentage data such as percentage of insect mortality were arcsine square root transformed before analyses to stabilize variances. However, untransformed data are reported in the manuscript. All t-tests were conducted using PROC TTEST.

3. Results

3.1. Temperature and moisture content

During the 7 h of the experiment, internal temperature in the SBHD was 52.3 ± 1.0 °C (range, 34.0–58.0 °C), for SD was 41.4 ± 0.8 °C (range, 30.3–50.0 °C), and in the laboratory it was 30.3 ± 0.2 °C (range, 28.6–31.4 °C). Temperatures in cages that held insects in the SBHD, under SD, and the laboratory were 49.6 ± 1.0 °C (range, 30.7–54.9 °C), 38.2 ± 0.6 °C (range, 29.3–43.3 °C), and 29.9 ± 0.2 °C (range 28.4–31.0 °C), respectively. In both internal conditions and cages, in the three locations (SBHD, SD, and Lab), temperatures were significantly different (df = 2,126 and $P<0.0001$ in both cases, whereas F values were 210.8 and 206.2, respectively). For both internal conditions and in cages, temperatures were always highest in the SBHD, followed by SD and lowest in the laboratory (Fig. 1A–C). Internal (52.3 ± 1.0 °C) and cage (49.6 ± 1.0 °C) SBHD temperatures were similar ($t = 1.92$, $P = 0.0588$).

Moisture content averaged was 15.9 ± 0.4% (range 12.6–20.3%) in the SBHD, 17.4 ± 0.3% (range, 15.1–20.3%) under SD, and 18.4 ± 0.2% (range, 16.8–20.3%) in the laboratory. There were differences in maize MC among the three locations (df = 2,117, $F = 18.5$, $P<0.0001$). The MC level was lowest in the SBHD, followed by SD, and was highest in the laboratory (Fig. 1A–C). Actual drop in MC in SBHD, SD, and laboratory conditions was 1.1% per hour (20.3–12.6%), 0.7% per hour (20.3–15.1%), and 0.4% per hour (20.3–17.4%).

3.2. Adult and immature insect mortality

There were differences in mortalities of *S. zeamais*, *T. castaneum*, and *C. ferrugineus* adults in SBHD, SD, and laboratory conditions (Table 1). In all cases, mortalities of insects of the three species were higher in the SBHD compared to SD and the lab. Numbers of immatures of *S. zeamais*, *T. castaneum*, and *C. ferrugineus* that developed into adults in the 500-g portions of maize in SBHD, SD, and laboratory conditions were different for each species (Table 1). In all cases, numbers of adults from 500-g portions of the maize were always highest in the laboratory, followed by SD, and were lowest in the SBHD. No insects were found in the three 500-g portions of pre-conditioned maize taken before the experiment, three 500-g portions taken directly from SBHD drying beds after the experiment, and another three 500-g portions taken after the experiment from the SD treatment tarpaulin (at no point had these nine 500-g portions been artificially infested) and had been incubated together with the other twenty-seven 500-g portions (these had been artificially infested).

3.3. Thermal cracking

There were no differences in the initial thermal (stress) cracking in the SBHD, SD, and laboratory (df = 2,6, F = 0.08, P = 0.9211). Initial thermal cracking values were 2.7 ± 0.9, 2.7 ± 0.3, and 2.3 ± 0.7 for the SBHD, SD, and laboratory, respectively. There were

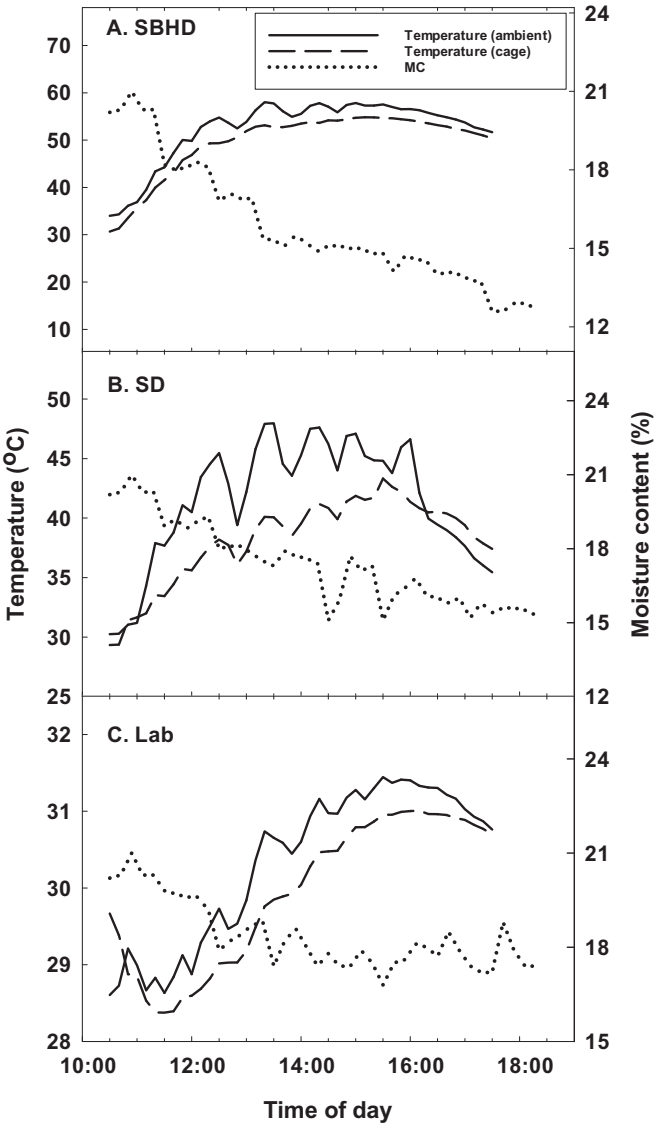

Fig. 1. Internal and cage temperatures, and also moisture content (MC) in solar biomass hybrid dryer (SBHD) (A), sun drying (SD) (B), and laboratory (C) conditions.

differences in thermal cracking for maize samples placed in SBHD, SD, and laboratory conditions ($df = 2,6$, $F = 13.8$, $P = 0.0057$). Thermal cracking values were 6.7 ± 0.9, 3.3 ± 0.3, and 2.7 ± 0.3 for the SBHD, SD, and laboratory, respectively. Thermal cracking was higher in the SBHD than in the SD and laboratory; there was no difference between the latter two.

4. Discussion

In this study, complete mortality of *S. zeamais* and *C. ferrugineus* adults was obtained in the SBHD treatment. This complete mortality achieved for *S. zeamais* and *C. ferrugineus* occurred despite the desired internal temperature of 50 °C having been maintained in the SBHD for only ~4 h. Usually a temperature of 50 °C is required for at least 6 h to kill all life stages of all stored product insect pests, in cases such as in this study where the layer of maize was only 1.3 cm deep (Opit et al., 2011). The most likely explanation for why the mortality of *T. castaneum* adults was 83.6% and not 100% was the fact that internal temperature conditions of 50 °C for 6 h were not attained. Opit et al. (2011) evaluated heat treatment against adults of *Rhyzopertha dominica* (F), *T. castaneum* and two species of psocids in empty concrete elevator silos and reported 98–100% adult insect mortality of these species when temperature was ~50 °C for 6 h. The results by Opit et al. (2011) clearly indicate that even *T. castaneum* is susceptible to heat as long as it is subjected to ~50 °C for 6 h. The response of stored product insects to elevated temperatures is influenced by species, developmental stages, acclimation and r.h. (Fields, 1992). It is important to note that development of heat tolerance is possible with slower heating rates in the SBHD, thus insects may become acclimatized to elevated temperatures within the 7-h treatment period and die more slowly (Lü and Liu, 2017). All life stages of *T. castaneum* are known to acclimate to elevated temperatures and this decreases their susceptibility to lethal high temperatures such as 50 °C (Lü and Liu, 2017). Perhaps acclimation is more pronounced in *T. castaneum* and may be the reason why 100% mortality did not occur.

Data from the present study showed that under conditions that existed in the SBHD, *T. castaneum* is much less susceptible to heat than *S. zeamais* and *C. ferrugineus*. Duration of exposure is a major contributor of heat mortality in insects, and the more extreme the temperature the shorter their survival. The fact that *S. zeamais*, the most destructive internal feeding insect pest of stored maize in Ghana, can be controlled under conditions of 50 °C for 4 h means the SBHD can be used to significantly contribute to post-harvest loss mitigation in Ghana. Operating the SBHD to achieve conditions of 50 °C for 6 h to effectively disinfest grain of all stored product insect pests can easily be accomplished given the abundance of biomass such agro-residues, timber scraps, etc. in Ghana.

It is worth noting that the 50 °C for 6 h conditions required for complete mortality of stored product insect pests were not achieved in the SD treatment throughout the experiment; the average temperature achieved in the SD treatment was 41 °C. Banks and Fields (1995) indicated that, above sub-lethal conditions (45 °C) most stored product insects die within 24 h, and at 50 °C insects die in less than 1 h. Given that lower temperatures were recorded in the cages in the SD treatment (38.2 °C) and laboratory (29.1 °C) conditions, low mortality of adult insects was expected (0–27%) and this explains why the normal practice of sun drying does not disinfest commodities.

In this study, immatures did survive the heat conditions in the SBHD and ultimately developed into adults 60 d after drying. Survival of immatures may be due to immature insect stages being more heat tolerant than the adults and/or that they are found inside maize kernels/particles or can burrow deep in the maize substrate, hence are insulated from the surrounding high temperature. Tolerance to heat, or ability to withstand elevated temperatures in insects is influenced by species, developmental age, and thermal acclimation among other factors (Dermott and Evans, 1978; Fields, 1992; Hallman and Denlinger, 1999). For example, Mahroof et al. (2003) reported that first instar *T. castaenum* were more heat tolerant at 50–58 °C than eggs, old larvae, pupae and adults, but Boina and Subramanyam (2004) showed that the old larvae of *T. confusum* were more heat tolerant than eggs, young larvae, pupae and adults at 46–60 °C. The maize in which the immatures are found apparently offered some protection for immature *S. zeamais*, *C. ferrugineus* and *T. castaenum*. Even though the target temperature of 50 °C was attained for 4 h, some immatures developed into adults even in the SBHD. This result where immatures survived to adult emphasizes the importance of maintaining 50 °C for 6 h to effectively disinfest grain. In fact, if complete mortality of immatures using the SBHD is desired, investigation of using heat treatment at 50 °C for 6 h or longer needs to be conducted.

Heat disinfestation can be more effectively achieved if temperature build-up is rapid and uniformly distributed. Given that the SBHD has a furnace that utilizes biomass and also uses solar

Table 1
Adult insect mortality (mean ± SE) and number of adults developing from 500-g maize portions in solar biomass hybrid dryer (SBHD), sun drying (SD) and laboratory (LAB) conditions. For each response variable, differences among drying methods within each species are denoted by lower-case letters, and significant differences within each drying method by species are denoted with different upper-case letters ($P<0.05$, LSMeans under Proc Mixed in SAS).

Response variable	Species	Drying method		
Adult mortality (%)		SBHD	SD	LAB
	S. zeamais	100.0 ± 0.0 aA	27.0 ± 4.8bA	1.7 ± 1.7 cA
	C. ferrugineus	100.0 ± 0.0 aA	6.8 ± 4.4bB	0.0 ± 0.0 cA
	T. castaneum	83.6 ± 5.7 aB	2.1 ± 2.1bB	0.0 ± 0.0bA
Number of adults from 500-g maize portions				
	S. zeamais	5.7 ± 0.3 cA	235.3 ± 15.7bA	600.7 ± 62.3 aB
	C. ferrugineus	8.7 ± 0.3 cA	212.3 ± 26.1bA	932.0 ± 29.1 aA
	T. castaneum	12.3 ± 1.2 cA	122.3 ± 11.3bB	165.07 ± 18.8 aC

In relation to insect mortality, ANOVA results for effects of species, drying method, and the interaction (species*drying method) showed they are all significant. ANOVA values for the main effects and interaction were df = 2,18, $F = 18.1$, $P<0.0001$; df = 2,18, $F = 419.4$, $P<0.0001$; and df = 4,18, $F = 4.8$, $P = 0.008$.
Similarly, in the case of number of adults developing from 500-g maize portions, ANOVA results for effects of species, drying method, and the interaction (species*drying method) showed they are all significant. ANOVA values for the main effects and interaction were df = 2,18, $F = 91.0$, $P<0.0001$; df = 2,18, $F = 355.3$, $P<0.0001$; and df = 4,18, $F = 65.4$, $P<0.0001$.

radiation, this rapid build-up of temperature can easily be achieved. This can be facilitated by having fans within the SBHD to efficiently circulate air and heat. Beckett and Qaisrani (2003) suggested that the best way to guarantee disinfestation of products is to heat up the system as rapidly as possible so that the desired temperature to get complete mortality is achieved in a timely fashion. Dosland et al. (2006) have stressed the importance of uniform heat distribution to avoid overheating and damage resulting from hot spots. Further, they explained that it operates to prevent insect escape to cooler areas and allows efficiency and effectiveness of heat disinfestation. The cost of rapidly raising temperature inside the SBHD for effective disinfestation can be greatly minimized if biomass such as maize cobs and husks can be combusted instead of wood to generate heat. Maize cobs and husks are considered environmental nuisance and would be free or inexpensive to access for heat generation in the SBHD.

Moisture content plays a significant role in storage of maize grain; it affects the quality of grain, allowable storage time and overall storage management of the grain. It is generally recommended that harvested maize be dried as quickly as possible to MC levels of 10–13% for storage (Hell and Mutegi, 2011; Danso et al., 2017). The actual drop rate in MC in SBHD, SD, and laboratory conditions was 1.1% per hour, 0.7% per hour, and 0.4% per hour, respectively. The difference in the drying rate could be attributed to the higher temperatures recorded in the SBHD compared to either SD or laboratory. The faster rate of drying observed in the SBHD could reduce the risk of mycotoxins. Hamiton (2000) demonstrated that drying harvested maize to 15.5% MC or lower within 24–48 h would reduce the risk of fungal multiplication and subsequent aflatoxin production. Moreover, the temperature range (34.0–58.0 °C) recorded in the SBHD for the drying duration was within the thermal threshold (55–60 °C) recommended for heat treatment of cereal grain to maintain processing quality (Brooker et al., 1974).

The high thermally damaged kernels (TDK %) recorded in the SBHD can be explained by the elevated temperatures recorded and drying time. Evans et al. (1983) reported that maximum kernel temperature and kernel residence time must be controlled to prevent damage to kernels during disinfestation. The percent TDK recorded under laboratory conditions can be attributed to thermal damage sustained by grains on-field because grain MC determined prior to conditioning process was about ~13.2%. The TDK would not be a serious issue in the case of maize destined for livestock feed or milling for flour.

The high average temperature of 52.3 °C that was recorded on the top drying bed of the SBHD could negatively impact maize kernels that are being dried for seed. In a study by Akowuah et al. (2018), maize dried at the upper level of the SBHD where the highest mean temperature of 52.8 ± 5.4 °C and the highest stress crack index (SCI) of 160 were recorded had a low seed percentage germination of 44%. However, the germination of maize dried at the lower levels was not affected (Akowuah et al., 2018). This implies that if maize for seed is dried in the SBHD, only the lower drying beds should be used. This reduction in percentage germination would not be an issue for maize being dried for livestock feed or milling for flour. It is important to note that lower layers or shelves in the SBHD might have a lower energy input for drying and, hence, the average drying rate likely lower than the those at the top. Similarly, the effect on insect mortality most likely is different in the different shelves.

The results of this experiment showed that the SBHD is effective for rapid drying of maize compared to SD and that it is possible to generate temperatures above 50 °C in SBHD to disinfest maize of stored product insect pests. Therefore, the SBHD can be an important tool for the management of insect pests and can be used alongside other control methods, specifically hermetic storage bags (PICS, ZeroFly® Hermetic Storage bags, etc). This could significantly mitigate post-harvest losses and improve food security. Future work should investigate the effects of maintaining conditions of 50 °C for 6 h or longer on survival of immature insects.

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