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Optimization of use of solar radiation exposure to control weevils (*Sitophilus zeamais*) in stored maize

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ABSTRACT

Maize (*Zea mays* L.) is a staple crop in many regions, but its postharvest storage is severely threatened by the maize weevil (*Sitophilus zeamais*), leading to significant grain losses. This study evaluated the efficacy of solar energy exposure as a non-chemical method to control maize weevils and preserve grain quality. The experiment investigated the effects of different solar exposure durations and frequencies on weevil mortality, grain weight loss and seed damage over a 90-day storage period. Treatments included exposing infested maize to direct sunlight for one (1), two (2) and three (3) hours and exposure frequencies once or twice per month. The treatments were compared against Shumba (a chemical control) and an untreated seed (negative control). Results revealed that solar exposure significantly increased the mortality rate of maize weevils ($p< 0.001$), with treatments such as 2 hours twice monthly (2H2M) and 3 hours twice monthly (3H2M) achieving mortality rates above 85% by the end of storage duration (90 days) similar to Shumba. Significant reduction in seed weight loss and seed damage ($p < 0.01$ to $p < 0.001$) were recorded in samples with higher exposure regimes. The untreated control demonstrated the highest losses, with weight loss reaching 14.84% and seed damage 35.67% by the end of exposure duration (90 days). The findings of this study, demonstrate that intermittent and sufficient exposure of maize seed to sun radiation can be a feasible strategy to manage maize weevil's infestations and preserve both quantity and quality of grain and seed. Solarization offers a sustainable, cost-effective alternative to chemical insecticides for smallholder farmers, especially in places with high solar intensity or poor access to expensive techniques.

Key words: Solarization, Solar intensity, Seed damage, Weight loss, Weevil's mortality

INTRODUCTION

Maize (*Zea mays* L.) is the most extensively cultivated staple grain crop in developing nations, playing a vital role in food security and economic development (Maziku, 2019, Suleiman *et al.*, 2016). In Tanzania, maize dominates agriculture, grown on over 45% of the country's arable land, across all 21 administrative regions. It serves as the principal source of income for rural communities, contributing close to 50% of their cash earnings (FAOSTAT, 2019). The crop's importance is further underscored by Tanzania's high per capita consumption of approximately 112.5 kg annually, translating to a national demand of around three million tons per year. Over two million hectares are dedicated to its cultivation, representing about 45% of total cropland. Maize simply forms the cornerstone of Tanzanian's subsistence and smallholder farming systems (Temu *et al.*, 2019).

Maize production in Tanzania is dominated by smallholder farmers who cultivate land under rain-fed conditions using traditional methods, limited mechanization, and minimal agrochemical input (Baijukya *et al.*, 2020). These farmers, typically managing plots of less than 10 hectares, contribute approximately 85% of national maize production (Temu *et al.*, 2019). Reliance on farmer-saved seeds is particularly high in East Africa, with over 60% of maize farmers reusing seeds from previous harvests for up to two years, often selected based on subjective preferences (Marimo *et al.*, 2021). Annually, Tanzania utilizes about 70,000 metric tons of maize seed, 80% of which is retained by farmers themselves (Wilson and Lewis, 2015). These saved seeds are typically stored for 6–8 months between harvest and the next planting season, during which time they are highly vulnerable to damage from insect pests, including such as *Sitophilus zeamais, Prostephanus truncatus, Tribolium castaneum, and Sitotroga cerealella* (Abass *et al.*, 2018: Cosmas *et al.*, 2018).

Among these pests, the maize weevil (*Sitophilus zeamais*) is one of the most damaging posing a serious threat not only to the quantity of stored grain but also to its quality, nutritional value, and viability (Cosmas *et al.*, 2018). S. *zeamais* alone is estimated to cause up to 40% of post-harvest grain losses in storage across developing regions (Phokwe and Manganyi, 2023). On smallholder farms, losses can reach 60%, especially when conventional storage methods like polypropylene woven bags and limited fumigation are used (Odjo *et al.*, 2020). Infestation by just two weevils per grain kernel can lead to nearly 18.3% loss within 48 days (Patino-Bayona *et al.*, 2021). Beyond the physical damage, these insects can introduce fungal pathogens like *Aspergillus flavus*, compromising food safety and human health (Phokwe and Manganyi, 2023).

Traditionally, chemical pesticides have been the primary pest control method for farmers. However, these synthetic solutions raise significant environmental and health concerns.

Misuse often due to lack of training and awareness exacerbates toxicity risks, contaminates water bodies, and threatens non-target organisms, including humans (Mamoon-ur-Rashid *et al.*, 2025; Phokwe and Manganyi, 2023). Studies indicate that over 80% of applied pesticides can contaminate surrounding ecosystems, harming wildlife and increasing health risks such as carcinogenesis, neurotoxicity, reproductive issues, and immunological disorders (Hassaan and El Nemr, 2020; Marcelino *et al.*, 2019). Consequently, integrated pest management (IPM) practices are increasingly promoted to reduce dependence on chemical solutions, aligning with global goals to halve pesticide use and associated risks by 2030 (Hamel *et al.*, 2020).

Amidst the push for sustainable solutions, solar energy has emerged as an innovative, environmentally friendly alternative for pest control. Solar radiation is widely accessible, renewable, and generates sufficient heat to suppress pest populations through thermal stress (Khanlari *et al.*, 2020; Emmanuel and Hassan, 2019). Solar disinfestation, already used in some tropical regions against seed-borne pests, exploits natural solar heat to drive insects from stored grains and eliminate eggs or larvae through desiccation and thermal death (Dasanal *et al.*, 2022). Studies show that high-temperature exposure under low-humidity can deform insect eggs, halt larval development, and reduce pest populations (Damena *et al.*, 2022). Insects subjected to sub-lethal thermal stress may also enter a heat stupor, increasing their susceptibility to environmental exposure and predation (Slabber and Chown, 2005).

Solar heating is reported as a less hazardous and safe method to control pests like *C. maculatus* in cowpeas (Adebayo and Anjorin, 2018). Furthermore, it has proven effective against various storage pests (e.g., bruchids in legumes) while preserving grain quality (Adebayo and Anjorin, 2018; Hansen *et al.*, 2011). Despite its potential, the application of solar energy specifically for controlling maize weevils (*Sitophilus zeamais*) in stored maize seeds particularly those intended for planting remains underexplored. Crucially, the optimal frequency and duration of direct solar exposure required for effective suppression of S. *zeamais* is unclear. In Tanzania, research on using direct sunlight to treat stored maize seeds is particularly limited.

Therefore, this study aims to determine the optimal frequency and duration of solar exposure required for effective maize weevils control, ultimately enhancing on-farm seed storage practices among smallholder farmers. This research will contribute significantly to developing sustainable pest management strategies that reduce dependence on synthetic pesticides, minimize health and environmental risks, and support the long-term viability of stored maize seeds. If effective, intermittent solar heating could offer smallholder farmers in Tanzania and other maize-dependent countries an affordable, farmer-friendly pest control innovation.

MATERIALS AND METHODS

Study area

The storage and solarization experiment was conducted in the African Seed Health Centre (ASHC) laboratory at Sokoine University of Agriculture (SUA) in Morogoro (6° 72' 56" S, 37° 32' 14" E)Tanzania, while germination test was conducted at TARI Dakawa Tissue culture labatory (6° 41'38"S and 37° 53' 54"E). The experiment was carried out for a period of three months from August to November 2024 under ambient storage conditions.

Seed source and preparation

Recycled saved maize seed of STUKA cultivar were harvested and purchased from small scale farmers in Mvomero Morogoro in July, 2024. The maize was cleaned and disinfested in the oven at 50 °C for 3 hours to kill any sources of the *S. zeamais* eggs which might still exist in the seed sample (Fawki *et al.*, 2022).

Culture of weevils and inoculation

Sitophilus zeamais were collected from infested maize grains in Morogoro and reared on 1 kg of maize grains in 1.5 L jars covered with netted cloth at room temperature. Parent weevils were transferred to fresh grain every seven days until a sufficient number of laboratory-reared weevils of known age was obtained (Abebe *et al.*, 2009). Twenty adults' maize weevils (10 males,10 females) were inoculated to 3kg of disinfested maize in each polypropylene bag.

The sex of weevils was identified basing on characteristics of the rostrum (Kumari *et al.*, 2022). The insects were allowed to stay on the stored grain for seven days prior to solar exposure to establish infestation.

Exposure to solar radiation

A three months' experiment was set in August, 2024 and ended in November 2024. The sun exposure was conducted in the afternoon, between mid-day (12:00 and 3:00 pm), as the sun rays become most intense on earth and thus leads to maximum sun radiation and maximum heat degrees following the procedure used by Sepe *et al.* (2023). The infested maize seed (3kg) were exposed to solar energy by spreading on 50 x 70 cm polypropylene bags for the duration of 1, 2 and 3 hours twice (after every 15 days) and once a month. No exposure (negative control) and Shumba (positive control) treatments were laid out in the laboratory and not exposed to solar heat throughout the storage duration.

Experimental design

The polypropylene bags were arranged on the pallet and then outside during sun exposure in a Completely Randomized Design (CRD) with three replications. The treatments were NS= No sun exposure; 1H2M=one-hour exposure twice a month; 1H1M= one-hour exposure once a month; 2H2M= two hours' exposure twice a month; 2H1H= two hours' exposure once a month; 3H2M= three hours' exposure twice a month; 3H1M= three hours' exposure once a month and Shumba (a positive control).

Data collection

Data were collected at intervals of 15 and 30 days over a three-month period. The data collected were number of dead and live weevils, weight loss and seed damage. Weevil mortality and number of dead and live weevils were recorded every 15 days.

The dead and live weevils

From each treatment replication, a 300 g maize seed sample was taken and placed in a container with a net cover to prevent insect escape. The number of dead and live weevils emerging from the sample were manually counted and recorded. The live adults were kept for treatment while the dead adults were counted and discarded, and the weevil mortality rate was assessed following the method described by Suleiman *et al.* (2018).

% mortality={(No. of dead weevils)/(Total no. of weevils)}×100

Seed damage

The number of damaged and intact seeds was recorded monthly. And the percentage of seed damage was calculated by taking a random sample of 100 seeds and counting the number with bored holes or other signs of damage caused by *S. zeamais*, as outlined by *Padmastri et al.* (2017).

% see damage={(Number of damage seed)/(Total no. of seed)}×100

Weight loss

Seed weight loss was measured every 30 days, and the percentage weight loss for each treatment was calculated using the Thousand Grain Weight (TGW) method, as described by *Parwada et al.* (2018).

% weight loss={(Initial TGW-Final TGW)/(Initial TGW)}×100

Data analysis

The collected data were analyzed using R statistical software (version 4.3.0). Analysis of variance (ANOVA) was conducted using the aov function. When significant differences were detected, mean separation was performed using Tukey's post hoc test, with compact letter displays generated by the multicompLetters function from the multcompView package. Bar plots were created using the ggplot2 package for graphical representation of the results.

RESULTS

Environmental conditions during the experiment

The environmental condition (temperature and solar intensity) of the specified date for the experiment in Morogoro was monitored. The parameter values were recorded in each time of solar exposure and twice per month from September to November 2024 (Fig. 1). The lowest average temperatures were 26.48 ºC at 2:00 pm in September and the highest was 32.32 ºC at 12:00 pm in November. The lowest average solar intensity was 767.2 KJ at 2:00 pm in September and the highest was 2366.8 KJ at 12:00 pm in November. Both temperature and solar intensity decreased gradually from 12:00 pm to 2:00 pm but increased gradually from September to November, and the highest temperature and solar intensity was observed in November at 12:00 pm.

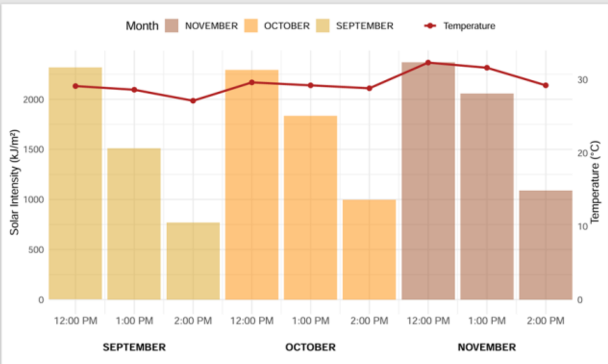

Fig. 1. Solar radiation intensity and ambient temperature recorded during solar exposure treatments of farm-saved maize seeds. The experiment was carried out at the African Seed Health Centre, Sokoine University of Agriculture, Morogoro, Tanzania. Data collected at Tanzania Meterological Authority (TMA) between September and November 2024

Table 1. Analysis of variance for mean square (MS) on the effects of solarization on weevil's mortality, weight loss and seed damage

Source of variation	df	Mortality (%)						Weight loss (%)			Seed damage (%)		
		15 days	30 days	45 days	60 days	75 days	90 days	30days	60 days	90 days	30 days	60 days	90 days
Treatment	7	2650.7***	2788.2***	2580***	3218***	3154.9***	3361***	5.283*	8.936**	18.542***	2.262**	42.71***	337***
Residual	16	80.7	104.9	91	166	139.2	26	1.525	1.808	0.723	0.5	2.38	14.9
Total	23	-	-	-	-	-	-	-	-	-	-	-	-

*= significant at 5%(p<0.05); **= significant at 1% (p<0.01) and; ***= Significant at 0.1 (p<0.001)

Table 2. The effects of solarization on mortality of maize weevils (*S. zeamais*)

Treatment	Mortality of maize weevils (%)					
	15 days	30 days	45 days	60 days	75 days	90 days
NS	6.67 d	0.00 c	3.72 c	4.03 b	4.96 b	4.50 b
1H1M	26.11 bd	63.89 a	63.49 a	72.22 a	86.67 a	100.00 a
1H2M	44.44 ab	68.06 a	71.03 a	88.89 a	91.67 a	100.00 a
2H1M	52.38 a	86.90 ab	73.61 ab	100.00 a	88.89 a	100.00 a
2H2M	50.00 ab	82.22 ab	85.00 ab	100.00 a	100.00 a	100.00 a
3H1M	54.60 a	85.00 ab	85.00 ab	80.56 a	100.00 a	91.67 a
3H2M	85.00 c	72.22 ab	85.00 ab	100.00 a	100.00 a	100.00 a
SHUMBA	100 c	100.00 b	100.00 b	100.00 a	100.00 a	100.00 a
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
CV (%)	56.06	43.5	41.11	41	38.69	37.08
SD	29.38	30.36	29.13	33.09	32.51	32.27
Grand mean	52.4	69.79	70.86	80.71	84.02	87.02

Means followed by the same letter in the column are not significantly different from each other at 5% Turkey's level of significant. S.E = Standard error, C.V = Coefficient of variation. *= significant at 5%(p<0.05); **= significant at 1% (p<0.01) and; ***= Significant at 0.1 (p<0.001), NS= No sun exposure; 1H2M=one-hour exposure twice a month; 1H1M= one-hour exposure once a month; 2H2M= two hours' exposure twice a month; 2H1H= two hours' exposure once a month; 3H2M= three hours' exposure twice a month; 3H1M= three hours' exposure once a month, SD=standard deviation, and CV=coefficient of variation.

Table 3. Effects of solarization on protection of maize weight loss due to weevils

Treatment	Weight loss (%)		
	30 days	60 days	90 days
SHUMBA	2.97 ab	4.11 ab	7.19 c
3H2M	1.83 a	3.20 a	7.99 ac
3H1M	4.22 ab	5.82 abc	11.53 b
2H2M	3.42 ab	4.91 abc	8.22 ac
2H1M	3.65 ab	6.51 abc	10.27 ab
1H2M	1.83 a	3.99 ab	10.05 ab
1H1M	4.91 ab	7.08 bc	11.64 b
NS	5.48 b	8.22 c	14.84 d
p-value	0.0187 *	0.00391 **	1.48e-07 ***
CV (%)	46.16	36.4	24.27
SD	1.63	1.99	2.48
Grand mean	3.54	5.48	10.22

Means followed by the same letter in the column are not significantly different from each other at 5% Turkey's level of significant. S.E = Standard error, C.V = Coefficient of variation. *= significant at 5%(p<0.05); **= significant at 1% (p<0.01) and; ***= Significant at 0.1 (p<0.001), NS= No sun exposure; 1H2M=one-hour exposure twice a month; 1H1M= one-hour exposure once a month; 2H2M= two hours' exposure twice a month; 2H1H= two hours' exposure once a month; 3H2M= three hours' exposure twice a month; 3H1M= three hours' exposure once a month, SD=standard deviation, and CV=coefficient of variation.

Analysis of variance

Table 1 presents the analysis of variance (ANOVA) for maize weevil mortality (%), seed weight loss (%), and seed damage (%) following intermittent solar exposure treatments.

Weevil mortality showed highly significant differences across treatments ($p < 0.001$) at all assessment intervals (15, 30, 45, 60, 75, and 90 days). Significant treatment effects were likewise observed for seed weight loss at 30 days ($p < 0.05$), 60 days ($p < 0.01$), and 90 days ($p < 0.001$), and for seed damage at 30 days ($p < 0.01$), 60 days ($p < 0.001$), and 90 days ($p < 0.001$).

Morality of weevils

At 15 days, 3H2M recorded the highest mean mortality (85%) among the tested treatments, which is statistically comparable to Shumba (100%). No exposure treatment recorded the lowest mortality (6.67%). The trend was observed consistently across 30 and 45 storage duration with higher mortality (63.5 – 85.00%) in treatments (2H1M, 2H2M, 3H1M, 3H2M) involving two or three hours of solar exposure (Table 2).

At 60 days, mortality reached 100% for 2H1M, 2H2M and 3H2M similar to Shumba while the No exposure recorded the lowest mortality (4.03%). The trend observed across 75 and 90 days where 100% mortality was recorded in 1H1M, 1H2M,2H1M, 2H2M and 3H2M similar to Shumba. Overall the mean percentage mortality ranged from 52-87% with substantial increase from 15 days of storage to 90 days across studied treatments. The highest coefficient of variation was identified at 15 days (56%) and lowest at 90 days (37%). No exposure consistently recorded lowest mortality below 5% while the mortality of most solar exposure treatments increased as the increase in storage durations.

Table 4. Effects of solarization on protection of weevil's damage on maize seeds

Treatment	Seed damage (%)		
	30 days	60 days	90 days
SHUMBA	0. 00 c	0.33 b	1.67 a
2H2M	1.00 ac	2.67 ab	3.33 a
3H2M	1.33 abc	3.67 ab	5.33 a
2H1M	1.67 abc	4.33 ab	12.33 a
3H1M	1.67 abc	3.67 ab	12.00 a
1H1M	2.00 ab	5.67 a	12.33 a
1H2M	2.00 ab	7.00 a	12.00 a
NS	3.00 b	13.00 c	35.67 b
p-value	0.00593 **	1.78e-06 ***	3.57e-07 ***
CV (%)	64.29	75.92	89.8
SD	1.02	3.83	10.63
Grand mean	1.58	5.04	11.83

Means followed by the same letter in the column are not significantly different from each other at 5% Turkey's level of significant. S.E = Standard error, C.V = Coefficient of variation. *= significant at 5%($p<0.05$); **= significant at 1% ($p<0.01$) and; ***= Significant at 0.1 ($p<0.001$), NS= No sun exposure; 1H2M=one-hour exposure twice a month; 1H1M= one-hour exposure once a month; 2H2M= two hours' exposure twice a month; 2H1H= two hours' exposure once a month; 3H2M= three hours' exposure twice a month; 3H1M= three hours' exposure once a month, SD=standard deviation, and CV=coefficient of variation.

Weight loss

The highest weight loss (5.48%) was observed in seeds which were not exposed to sun (No Exposure treatment (NS)) and the lowest weight loss recorded in 1H2M and 3H2M each with 1.83%. All other solar exposure treatments recorded weight loss between 2.97% and 4.91% which is statistically comparable to Shumba at $p<0.05$ ($p=0.0187$).

By 60 days, the progressive increase in weight loss (8.22%) were recorded in NS treatment while 3H2M (3.20%) recorded the lowest weight loss followed by 1H2M (3.99%). There was non-statistical difference in mean percentage weight loss between NS (8.22%) and 1H1M (7.08%) treatments ($p=0.00391$) but NS varied significantly with rest of the treatments (Table 3).

At 90 days, NS mean weight loss was 14.84% significantly higher than any other treatments (p<0.001). 2H1M, 1H2M, 1H1M and 3H1M were statically similar with mean weight loss of 10.27, 10.05, 11.64 and 11.53% respectively. The percentage weight loss for SHUMBA, 3H2M and 2H2M were the lowest and statistically not significant with 7.19, 7.99 and 8.22 respectively. The grand mean weight loss percentage was lowest at 30 days (3.54%), followed by 5.48 and 10.22% at 60 and 90 days respectively. Generally, the trend shows high increase in weight loss with storage duration in untreated treatment than in solar exposure treatments.

Seed damage

The mean seed damage percentage at 30, 60 and 90 days are displayed in Table 4. At 30 days, the highest mean seed damage (3.00%) was recorded in NS treatment while no damage was recorded in Shumba (0.00%). Treatments, 3H2M, 2H1M, 3H1M, 1H1M, 1H2M and NS with corresponding mean of 1.33, 1.67, 1.67, 2.00, 2.00 and 3.00% respectively, were statically similar. NS significantly differed with SHUMBA (0.00%) and 2H2M (1.00) seed damage percentage (p<0.01).

At 60 days, the Seed damage in the NS treatment accelerated to 13.00% which is significantly higher than all other treatments (p < 0.001). Treatments with higher frequency and long duration of exposure like 2H2M (2.67%), 3H2M and 3H1M (3.67% each) demonstrated the lower damage which is statistically comparable to Shumba (0.33%).

Contrary, shorter and less frequent exposures such as 1H2M (7.00%) and 1H1M (5.67) recorded increased seed damage which is significant higher than Shumba (0.33%) but lower than NS treatment (13.00%).

At 90 days, the variation among treatments were more noticeable. NS consistently recorded the highest damage (35.67%), while all solar exposure treatments particularly 2H2M (3.33%) and 3H2M (5.33%) recorded lower damage statistically comparable to Shumba (1.67%).

The damage in treatments with short duration and less frequency of exposure like 1H1M, 2H1M, and 1H2M progressively extended up to 12.33% but still significantly lower than the untreated control. The trend shows the gap in increase of seed damage between the NS and treatment with low exposure and less exposure to those with long time and high exposure frequency. Overall grand mean and CVs were in progressive trend lowest at 30 days (grand mean 1.58, CV 64.29%) and highest at 90 days (grand mean 11.83, CV 89.8).

Statistical analysis evidenced highly significant treatment effects (p < 0.01 to p < 0.001), particularly as infestation progressed. Coefficients of variation (CV) were high particularly at 90 days (89.8%) reflecting increasing difference in treatment performance over time. The grand mean seed damage increased from 1.58% at 30 days to 11.83% at 90 days, underscoring the cumulative impact of infestation in untreated treatment across the storage duration implying the importance of effective control measures.

DISCUSSION

The results of this study reveal that solarization is an effective natural method for protecting seed against storage pests, particularly maize weevils with both exposure frequency and duration of exposure playing a critical role in achieving high mortality rates. Treatments with longer and more frequent exposure to solar energy resulted in significantly higher mortality of maize weevils, reduced seed weight loss and lower seed damage compared to those with shorter and less frequent exposure. Solar exposure treatments like 2H2M, 3H1M and 3H2M achieved high mortality by 60 days of storage. This indicate the potential of solarization as a viable natural pest control method alternative to chemicals (Shumba). The effectiveness could be attributed to the lethal effects of solar intensity on the insects. By 90 days, substantial mortality was also recorded in treatments with shorter and less frequent exposure like 1H1M, suggesting that solarization remains effective even with minimal intervention. However, treatments with higher exposure intensity, such as 3H2M and 2H2M, produced rapid and sustained control, reaching 85–100% mortality within the early storage period (45–60 days) and maintaining this effectiveness throughout the storage period.

Prolonged solar exposure is likely to accelerate seed temperature to levels that may be lethal to the eggs and adult maize weevils, disrupts their reproductive cycles, cause desiccation or denature pest's essential amino acids. Previous studies corroborate these findings: Akuba *et al.* (2023) reported that solar radiation alone is lethal to a wide range of insect pests of stored products. Adebayo and Anjorin (2018) found significantly higher mortality of *Callosobruchus maculatus* in cowpeas after 3 hours of solar exposure, demonstrating the effectiveness of 1–3 hours of treatment in reducing bruchid survival and protecting cowpea seeds. Asemu *et al.* (2020) reported the lowest number of live insects were recorded in open sun dried grains after the 6 months of storage while, Asemu *et al.* (2020) observed the lowest insect counts in open sun-dried grains after six months of storage. Ajayi *et al.* (2021) further highlighted that, solar heat enhanced with black propylene sheets resulted in higher mortality of both adult and immature stages of *C. maculatus* compared to ambient conditions.

Similarly, Damena *et al.* (2022) reported complete inactivation of maize weevil eggs and adults when exposed to 60 °C for 2 hours.

The untreated (control) recorded the highest weight losses throughout storage, emphasizing the destructive potential of maize weevils when grain is left unprotected. In contrast, the lowest weight loss was consistently observed in the 3H2M treatment, performing comparably to the chemical control (Shumba). This outcome reinforces earlier mortality findings and highlights the effectiveness of frequent and prolonged solar exposure in protecting seed from infestation. Other treatments, such as 2H2M and 1H2M, also minimized weight loss, demonstrating that increasing either the duration or frequency of exposure can provide substantial protection. High-intensity exposures appeared to slow the progression of damage by suppressing weevil feeding and reproduction. Conversely, minimal exposure regimes (e.g., 1H1M) were associated with significantly greater weight loss, indicating that low-intensity solar treatments are insufficient to disrupt weevil activity within seeds. These results align with previous studies: Akuba *et al.* (2023) reported significantly less weight loss in cowpea grains exposed to sunlight compared to laboratory conditions, while Adebayo and Anjorin (2018) found that three hours of solar treatment minimized cowpea weight loss by reducing adult emergence and feeding damage.

Seed damage followed a similar trend whereby, the untreated control exhibited a sharp increase in damage, rising from 3.00% at 30 days to 35.67% at 90 days, reflecting unchecked weevil population growth. This pattern is consistent with Padmasri *et al.* (2022), who observed that damage generally increases with storage time due to expanding pest populations. Among solar treatments, 2H2M and 3H2M consistently recorded the lowest seed damage, statistically comparable to Shumba, confirming the efficacy of longer and more frequent exposures. In contrast, treatments with either shorter or less frequent exposures (e.g., 1H1M, 2H1M, 1H2M) resulted in significantly greater seed damage. These regimes likely failed to eliminate internal life stages or prevent egg-laying and larval development, allowing pests to continue feeding within seeds. The chemical control (Shumba) provided the best protection, maintaining damage below 1.67% throughout storage.

These findings reinforce mortality patterns, suggesting that higher frequency and longer solar exposures suppress feeding, reproduction, and larval development, thereby limiting seed injury. Similar results have been reported elsewhere: Padmasri *et al.* (2022) found the lowest infestation levels in green gram seeds solarized for three hours, while Chauhan (2022) noted that solar heating completely eliminated bruchids and protected cowpea seeds. Emmanuel and Hassan (2019) also demonstrated reduced progeny development in cowpea bruchids exposed to solar radiation under black polypropylene sheets. Likewise, Adebayo and Anjorin (2018) observed that longer exposures significantly reduced feeding damage, egg-laying, and seed perforation. Padmasri *et al.* (2022) further reported that solarizing green gram seeds for three hours daily over six days limited insect damage to only 0.49%, compared with 8.17% in untreated controls. Overall, this study confirms that solarization is effective in controlling storage insect pests, minimizing weight loss, and reducing seed damage. By preserving grain quantity and safeguarding quality attributes such as viability, taste, and market value, solarization provides a promising, low-cost, and environmentally friendly alternative to synthetic insecticides such as Shumba, which pose risks to human health.

CONCLUSION

This study demonstrates that solarization is a practical, low-cost, and eco-friendly method for managing maize weevils during storage. By significantly causing mortality of weevils, reducing seed weight loss and internal damage, solarization helps preserve grain quantity and quality, making it particularly suitable for smallholder farmers with limited access to synthetic pesticides. Although environmental factors such as temperature and grain thickness may influence its effectiveness, the consistent performance across treatments highlights its potential as a reliable alternative to chemical control. To enhance its impact, future research should focus on optimizing key parameters such as seed layer thickness and storage material.

Promoting solarization through farmer education and integration into broader pest management strategies can play a vital role in reducing postharvest losses and improving food security.

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