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Full Length Research Paper

High-density polyethylene containers and super grain bag reduce storage insect pests' infestation in maize and preserve grain quality

Rafael José Nguenha[1]*, Lucas Daniel Tivana[1], Paula da Conceição M. Viola[1], Isabel João B. Monjane[2], Sandra Salvador I. Chemane[1], Nswana Kanfwanfwa[3], Dovel Branquinho Ernesto[4] and Olipa N. Lungu[5]

[1]Universidade Eduardo Mondlane (UEM), Faculdade de Agronomia e Engenharia Florestal, Campus Universitário Principal, Av. Julius Nyerere, 3453, Maputo 1102, Mozambique.
[2]Instituto de Investigação Agrária de Moçambique, P. O. Box 3658, Av. FPLM 2698, Maputo, Mozambique.
[3]Zambia Agriculture Research Institute–ZARI, Mochipapa-Choma, Zambia.
[4]Instituto Superior Politécnico de Manica, Agriculture Division, Campus de Matsinho, Manica 2203, Mozambique.
[5]University of Zambia, School of Agricultural Sciences, Great East Road Campus, P. O. Box 32379, Lusaka, Zambia.

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The study evaluated the performance of polypropylene bag (PP), polyethylene drum (PD), polyethylene silo tank (PST), and super grain bag (SGB) on preserving maize quality. The trials were conducted on-station and on-farm. Insect density, grain damage, weight loss, and grain moisture content were determined monthly for six months for on-station trials. For on-farm, insect density and grain damage were assessed every two months for eight months, and the acceptability test of the grain was performed after the storage period. The initial insect density of the grain was 26 insects/kg (natural infestation), and the percentage of damaged grain was 1.6%. After six months, for grain stored in PP, the insect density increased by 31-fold, whereas damaged grain increased by 10-fold, resulting in a 31-fold increase in grain weight loss. In contrast, the insect density did not increase significantly in SGB, PD, and PST over six months of storage. Grain stored in SGB presented the highest acceptability, while grain stored in PP was considered unfit for human consumption. The on-farm trials confirmed the effectiveness of the SGB, PD and PST on minimizing insects' multiplication and grain loss, making them suitable for reducing maize losses during long-term storage under smallholder farmers' conditions.

Key words: Grain loss, hermetic storage, insect pests, on-farm, sensory evaluation.

INTRODUCTION

Maize is a major staple food crop and a key source of protein and calories in several sub-Sahara African

*Corresponding author. E-mail: rafaelnguenha@gmail.com. Tel: +258 85 564 0587.

countries. This crop is mostly produced by smallholder farmers under rain-fed conditions. During storage, maize is heavily attacked by insects, resulting in high post-harvest losses which amounts to 30% or more (Njoroge et al., 2014; Abass et al., 2018; Mutambuki et al., 2019). Post-harvest losses reduce the food available for household consumption directly impacting food security status (Ognakossan et al., 2013; Chegere et al., 2020). To avoid losses, farmers tend to sell their grain just after harvest, when market prices are low due to high supply, incurring losses of income (Kadjo et al., 2018; Baributsa and Cristine, 2020).

Smallholder farmers in sub-Saharan Africa (SSA) store their grains in traditional containers such as polypropylene bags, granaries, clay containers and baskets (Gitonga et al., 2013; Abass et al., 2014; Bwambale et al., 2020). These containers can be easily infested and therefore are unable to prevent the action of post-harvest pests (Baoua et al., 2014; Bwambale et al., 2020; Luo et al., 2022). Synthetic pesticides such as Actellic® dust (Pirimiphos-methyl (1.6%) + Permethrin (0.3%)) and Sofagrain® (Pirimiphos-methyl (1.5%) + Deltamethrin (0.5%)) have been used to control insect infestation in stored grain (Njoroge et al., 2014). However, the use of chemicals is hampered by increasing reports of reduced efficacy due to development of pest resistance (Collins, 2006), environmental and health-related problems (Sola et al., 2014; Lane and Woloshuk, 2017), adulteration and misuse (Baributsa et al., 2010; Mutambuki et al., 2019), as well as the high costs and low availability of these products in rural areas of developing countries (Tefera et al., 2011; Ognakossan et al., 2013). Therefore, there is an emerging need for alternatives over pesticide to control insect pests. Hermetic storage technology has been widely proposed as a simple, environmentally friendly, and cost-effective strategy to reduce grain loss during storage, with a positive impact in household food and income security (Shee et al., 2019).

Hermetic technology is based on the exchange's reduction of gas between the inside and the outside of the storage structure. The continuing respiration of the grains, moulds and insects within the storage structure leads to the depletion of oxygen and accumulation of carbon dioxide. These conditions limit the development and reproduction of aerobic fungi and insects minimizing grain damage and loss during storage (Walker et al., 2018).

Hermetic systems such as Purdue Improved Crop Storage (PICS), Super Grain bags (SGB^{TM}) and metal silos have been shown effective against insect pest during storage. Baoua et al. (2013) demonstrated that SGB and PICS bags equally protect cowpea grain from being infested by *Callosobruchus maculatus* for four months of storage, with no significant damage on grain, while severe grain damage occurred in woven polypropylene bags. However, the author observed that the SGB had several holes made by the bruchid from inside and outside the bags. Baributsa et al. (2020) evaluated the performance of several hermetic bags, including SGB and PICS, against storage insect pests on maize. In another study, Likhayo et al. (2016) observed that metal silos and Super Grain Bags supressed insect population on stored maize, leading to a weight loss below 2%, whereas in polypropylene bags weight loss as high as 32% was registered after nine months of storage.

The use of high-density polyethylene containers, which are widely available, could be an alternative for hermetic storage provided that the container is properly sealed. Covele et al. (2020) observed a reduction of insect population by 70% after 12 months of paddy rice storage, whilst the number of insect pests in polypropylene bags increased by 200% at the same period.

Although several studies have been conducted to evaluate the performance of hermetic containers against insect pests during grain storage, most have been conducted under laboratory conditions and for six months or shorter periods. Moreover, the farmers' perceptions regarding the quality of the grain post-storage have been neglected. Considering that farmers in Africa need to store their grain until the next harvesting period, it is crucial to evaluate these containers at farmers' conditions and management practices for over six months. Accordingly, this study aims to evaluate the performance of hermetic containers, such as Super Grain Bag, Polyethylene Drum, and Polyethylene Silo Tank, as alternatives to chemical pesticides in protecting maize grain and minimizing losses during storage for six months *on-station* and eight months *on-farm* farmers conditions. Additionally, farmers' perception of grain quality was evaluated after eight months of storage.

MATERIALS AND METHODS

Experimental sites

On-station trials were conducted at the Agricultural Engineering Section of Eduardo Mondlane University, in Maputo City, Mozambique. The trials were conducted over six months, from August 2020 to January 2021.

The experiment was also conducted on-farm, to test the appropriateness of the containers under realistic smallholder management conditions. In this sense, the *on-farm* trials were conducted in two districts of Manica Province, Vanduzi and Sussundenga, with similar agro-ecological conditions. Three localities were selected for the trials in each district, namely Chitundo, Belas and Selva in Vanduzi and Munhinga, Sussundenga Sede and Rotanda in Sussundenga.

Maize grain origin and variety

For *on-station* experiments, the grain (Matuba variety) was purchased from Umbeluzi Agricultural Research Station in Boane district. The selected variety is one of the most used by smallholder farmers in South of Mozambique, where the experiment was conducted.

On the other hand, mixed grain (unknown varieties) from

A B C

Figure 1. Hermetic containers evaluated in the trials; A – Polyethylene Silo Tank; B – Polyethylene Drum; C – Super Grain Bag inside a polypropylene woven bag.
Source: Author

smallholder farmers was used for *on-farm* trials. Before the grain was loaded to the storage structure, it was thoroughly mixed for uniformity and divided into equal amounts for each farmer. All the grain used was harvested no more than two months before the experiments.

Treatment description and experimental set up

Eight treatments were evaluated for *on-station* trials: (1) polypropylene woven bag (control - PP); (2) polypropylene woven bag with Actellic® dust (PP-A), (3) Super Grain Bag (SGB); (4) Super Grain Bag with Actellic® dust (SGB-A); (5) polyethylene drum (PD); (6) polyethylene drum with Actellic® dust (PD-A); (7) polyethylene silo tank (PST); and (8) Polyethylene Silo Tank with Actellic® dust (PST-A). Super Grain Bags and polypropylene bags were filled with 50 kg of maize grain, polyethylene drums with 210 kg, while polyethylene silo tanks were filled with 750 kg of maize grain.

Super Grain Bag (Figure 1C) was manufactured by *Grain Pro, Inc.* (Washington, United States of America), whereas both polyethylene containers (Figure 1A and B) were produced by *Plastex Lda.* (Maputo, Mozambique). The polyethylene containers are originally used for water storage, and the polyethylene silo tank was adapted by increasing the outlet hole to facilitate grain outflow.

Three containers of each type were used for the treatments, representing three replicates per treatment. To protect the Super Grain Bag against puncture and damage during handling, the bags were placed into the polypropylene bags, as recommended by the manufacturer. The storage containers were placed on pallets inside a warehouse at ambient conditions, using a randomised complete design.

For *on-farm* trials, Actellic® dust and polyethylene silo tanks were not included as treatments. Therefore, the treatments evaluated in *on-farm* trials were: (1) polypropylene bag; (2) Super Grain Bag; (3) polyethylene drum.

On-farm trials were conducted for eight months and grain sampling for analysis was done every two months. A total of 18 smallholder farmers randomly selected were involved in the trials, nine farmers in each district. Each farmer was attributed one container of each type, which was considered a repetition, totaling nine repetitions per container for the selected districts.

Grain sampling

Grain sampling for analysis was conducted as described in ISO-24333:2009 Cereals and cereal products – Sampling. Four sub-samples of 250 g each were taken from the top, middle, and bottom of the storage containers using double tube sampling spears and mixed thoroughly totaling 1.0 kg of maize grain. The moisture content of the grain used in *on-farm* was determined only at the beginning of the experiment to ensure that the grain used was adequately dried. For *on-farm* trials, insect density and grain damage were measured on the field in the presence of participating farmers. The two selected parameters can easily be understood by farmers, which is essential to demonstrate the difference among evaluated storage containers.

Insect population and grain damage assessment

Mean insect density

Insects were collected from 1.0 kg of composite sample and counted using standard approaches. Briefly, insects were separated from the sample and counted manually. Damaged maize grain was opened to remove insects lodged inside. Insect density was recorded by dividing the number of adult insects (live and dead altogether) by the grain sample weight. The insects were identified to species level using a combination of taxonomic keys and expert knowledge.

Grain damage and weight loss

Grain weight loss was assessed using count and weight method as described by Adams and Schulten (1978). Briefly, three replicates of 1000 grains were taken randomly from the working sample. The grain was cleaned to remove dust and foreign matters. After cleaning, the samples were examined using a hand magnifier and separated into two groups: (i) damaged grain by insects (observed by the presence of holes or burrows), and (ii) undamaged grain. Each group was counted and weighted. Then, the percentage of damaged grain and weight loss was calculated using (1) and (2) respectively:

$$\% \text{ of damaged grain} = \frac{b}{e} \quad (1)$$

where *b* is the number of damaged grains and *e* the total number of grains.

$$\% \text{ of weight loss} = \frac{(ab)-(cd)}{a(d+b)} \text{x}100 \quad (2)$$

where *a* is the weight of undamaged grains, *b* the number of damaged grains, *c* the weight of damaged grains, *d* the number of undamaged grains and *e* the total number of grains.

Grain moisture content

Moisture content was determined as described in the ISO-712:2009 Cereals and cereal products – Determination of moisture content – Reference method. Three subsamples of 5 g per replication were collected, dried in an oven at 105°C to constant weight, for at least 3 h, and then reweighed.

Sensory evaluation of stored grain

Sensory evaluation was conducted after eight months for the grain from *on-farm* storage in the districts where the trials were undertaken. Grain from different storage containers was submitted to the acceptability test among local smallholder farmers, including those participating in the trials. A total of 95 participated in the sensory evaluation to test the appearance of the grain after the storage period using the “Attribute Difference Tests” hedonic ratings ranging from 1 (dislike very much, very bad appearance) to 9 (like very much, very good appearance). A rating of 7 points represents grain of moderately good appearance.

Temperature and relative humidity monitoring

Temperature inside the storage containers was monitored using a thermocouple data logger (USB TC-08, Pico Technology, Cambridgeshire, United Kingdom). Relative humidity measurement was monitored using a thermo-hygrometer data logger (RH10, Extech, New Hampshire, USA).

Data analysis

Data were organized using Microsoft Excel (2020) and analyzed using SPSS 28.0 software (IBM, Armonk, New York, USA). The effect of storage containers on insect density, grain damage and weight loss, and grain moisture content along the storage period was examined using repeated measures ANOVA. Moreover, regression analysis was used to evaluate the effect of storage time on the same variables. ANOVA was also applied to test the effect of storage containers on consumer's attribute scores in sensory evaluation test. When significant differences were observed, Tukey's multiple comparisons test was used to separate treatment means. All tests were conducted at a 95% confidence level.

RESULTS

On-station experiment

Mean insect density

Four insect species were identified during the storage period: *Sitophilus zeamais*, *Rhyzopertha dominica*, *Sitotroga cerealella*, and *Tribolium castaneum*. *S. zeamais* was the most predominant insect species throughout the storage period, with 82.8% relative abundance at the beginning of the experiment and 63.8% after 180 days of storage. On the other hand, *T. castaneum* was not detected at the beginning of the experiment. However, its incidence showed an increasing trend after 120 days of storage, achieving a maximum of 24.8% at the end of the experiment. All insect species had the highest number in polypropylene bags without actellic.”

The initial mean density of insects was 26.1 individuals/kg of maize grain. The interaction effect between the storage container and storage period was significant ($F_{47,287} = 228$, $P < 0.001$). In all sampling periods, the polypropylene bags without actellic presented the highest insect density ($F_{7,143} = 877$, $P < 0.05$) compared to hermetic and polypropylene containers with actellic (Figure 2). In polypropylene bags, the number of insects increased significantly along the storage period ($F_{5,143} = 160$, $P < 0.05$), with about 150% increase after just 30 days of storage. However, no significant increase in the number of insects was observed in hermetic containers and polypropylene bags with the insecticide under the same storage period.

After 120 days of storage, the number of insects in polypropylene bags without the insecticide actellic increased by about 15-fold compared to the initial period, while for hermetic containers a significant increase in insect population was only observed for the grain stored in polyethylene silo tank, with 62% increase. For hermetic containers, actellic did not result in a significant improvement in the performance against insect multiplication over the storage period. Nevertheless, for polypropylene bags, the insecticide actellic provided significant protection against insects in the first four months, but a significant increase by 3-fold was observed from there to the end of the trials ($F_{1,17} = 66$, $P < 0.001$).

Percentage of damaged grain

The percentage of damaged grain at the beginning of the experiment was 7.4%. The percentage of damaged grain in polypropylene bag without actellic increased

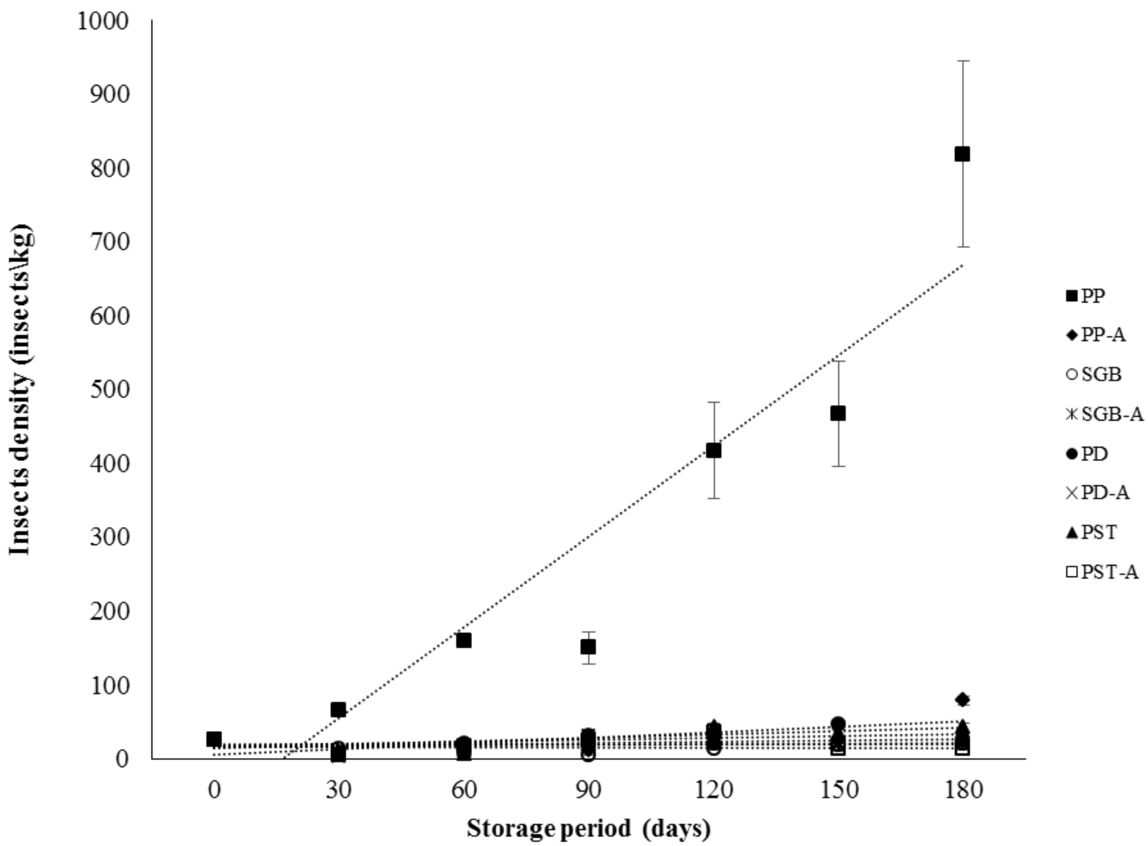

Figure 2. Mean insect density as a function of time (days) stored in different containers. PP = Polypropylene bag; PP-A = polypropylene bag + Actellic dust; SGB = Super Grain Bag; SGB-A = Super Grain Bag + Actellic dust; PD = polyethylene drum; PD-A = polyethylene drum + Actellic dust; PST= polyethylene silo tank; PST-A = polyethylene silo tank + Actellic dust. The height of the bars represents the magnitude of the standard deviation, with larger bars indicating higher variability.
Source: Author

significantly ($F_{5,17}$ = 97.7, P < 0.05) after 60 days of storage in polypropylene bags, achieving the highest value at the end of the storage period (180 days), with 74.8% of damaged grain, which represent an increase by 10-fold of the initial percentage of damaged grain (Figure 3). On the other hand, for hermetic containers and polypropylene bag with the pesticide, the percentage of damaged grain was stable in the first three months (90 days) of storage with no differences amongst the storage containers (Figure 3). Contrarily, the Super Grain Bag with and without actellic registered less damaged grain, with only 83.7% increase when compared to the initial period.

Percentage of weight loss

The initial percentage of weight loss was about 1.6%. In the first 30 days of storage, the weight loss did not change significantly ($F_{7,23}$ = 0.9, P = 0.99) in all storage containers (Figure 4). Nevertheless, after 30 days of storage, the polypropylene container without the insecticide showed an increasing trend up to the end of the experiment, with a 31-fold increase throughout the storage period. As per storage containers, the grain held in polypropylene bags without actellic presented the highest level of loss compared to other treatments (Figure 4).

When actellic was used in polypropylene container, it prevented a significant increase of weight loss in the first 60 days of storage, but from there onwards the grain loss increased significantly by about 7-fold compared to the initial period. Super Grain Bags and polyethylene silo tank showed the least increase in the percentage of weight loss throughout the storage period, while the polyethylene container without the pesticide showed the highest increase amongst the hermetic containers, with a 4-fold increase after 150 days of storage (Figure 4).

Moisture content of maize grain

The initial moisture content of the maize grain used in the experiment was about 12.7%, and did not change

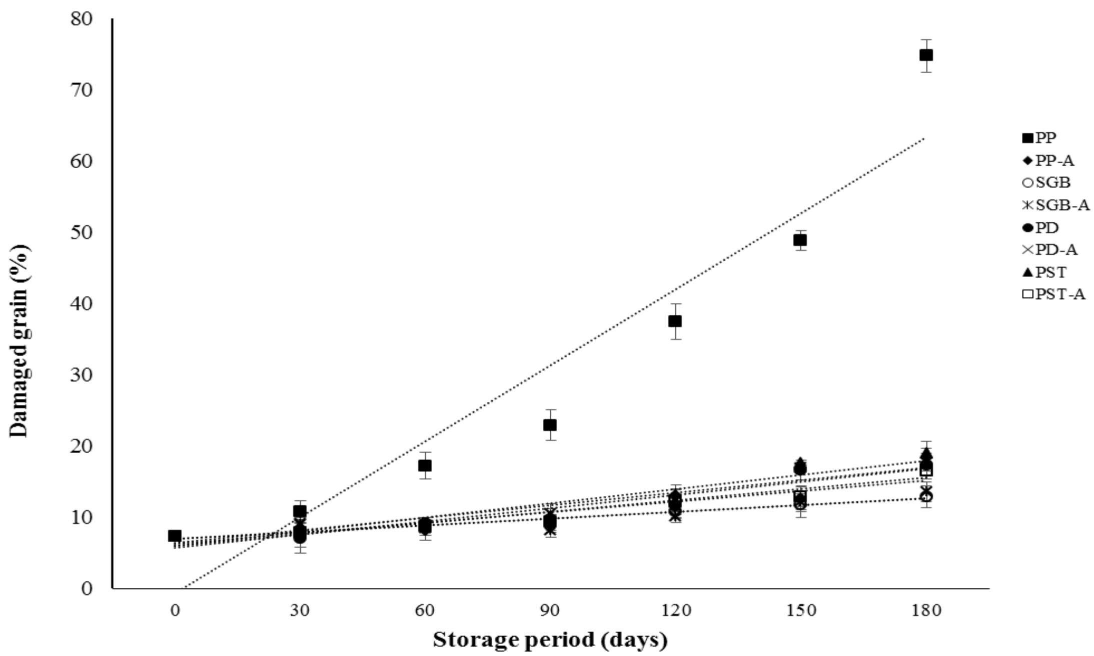

Figure 3. Percentage of damaged grain as a function of time (days) stored in different containers. PP = polypropylene bag; PP-A = polypropylene bag + Actellic dust; SGB = Super Grain Bag; SGB-A = Super Grain Bag + Actellic dust; PD = polyethylene drum; PD-A = polyethylene drum + Actellic dust; PST= polyethylene silo tank; PST-A = polyethylene silo tank + Actellic dust. The height of the bars represents the magnitude of the standard deviation, with larger bars indicating higher variability.
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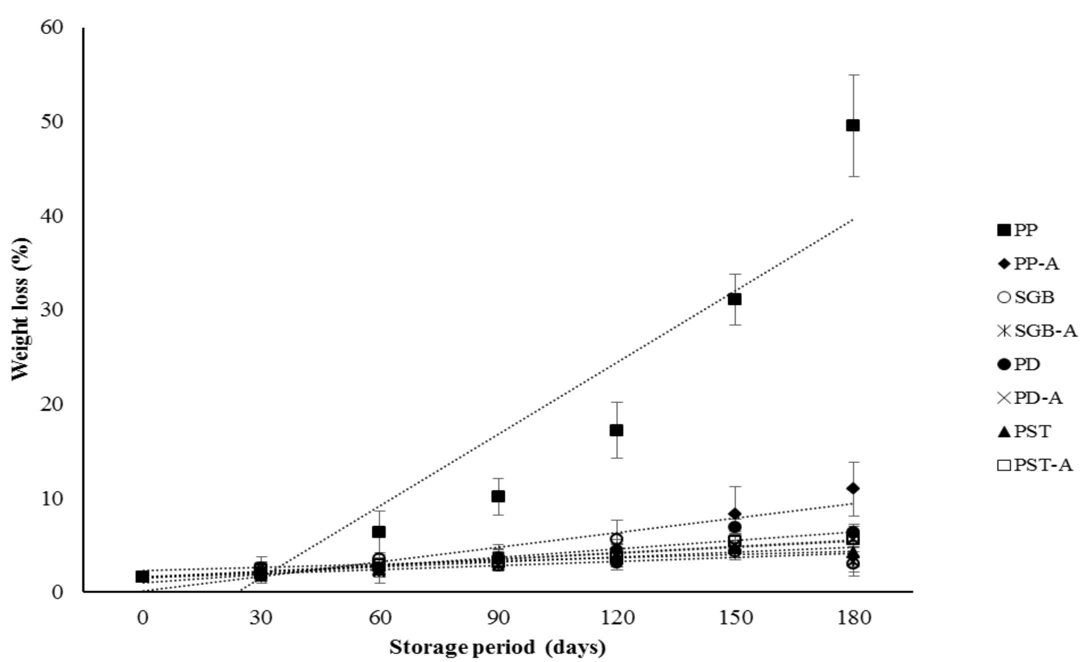

Figure 4. Grain weight loss as a function of time (days) stored in different containers. PP = Polypropylene bag; PP-A = polypropylene bag + Actellic dust; SGB = Super Grain Bag; SGB-A = Super Grain Bag + Actellic dust; PD = polyethylene drum; PD-A = polyethylene drum + Actellic dust; PST= polyethylene silo tank; PST-A = polyethylene silo tank + Actellic dust. The height of the bars represents the magnitude of the standard deviation, with larger bars indicating higher variability.
Source: Author

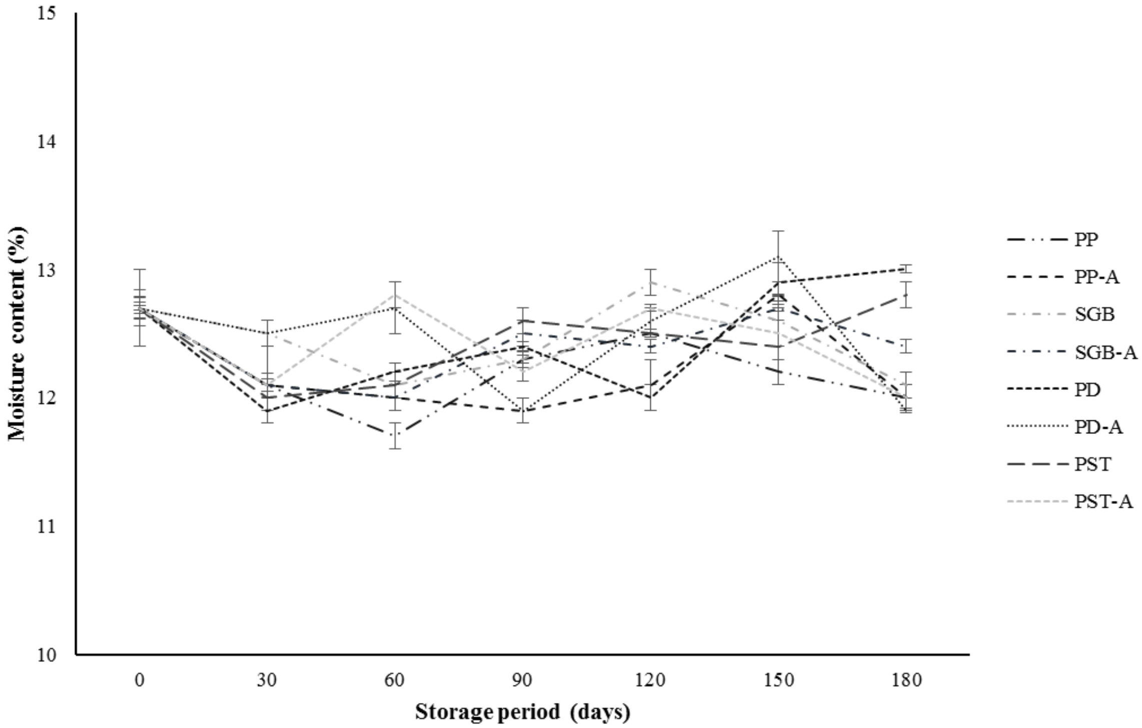

Figure 5. Moisture content of the maize grain stored in different storage containers for 180 days. PP = Polypropylene bag; PP-A = polypropylene bag + Actellic dust; SGB = Super Grain Bag; SGB-A = super grain bag + Actellic dust; PD = polyethylene drum; PD-A = polyethylene drum + Actellic dust; PST= polyethylene silo tank; PST-A = polyethylene silo tank + Actellic dust.
Source: Author

significantly ($F_{7,143}$ = 2.1, P = 0.6) throughout the storage period for all storage containers (Figure 5).

Temperature and relative humidity inside the storage containers

Temperature and relative humidity showed a similar trend in all storage containers under evaluation throughout the storage period (Figures 6 and 7). The temperature showed an increasing trend along the storage period, whereas the relative humidity was relatively stable. Regarding relative humidity, the polyethylene silo tank showed slightly the lowest values in the end of the experiment.

On-farm experiments

The moisture content of the grain varied between 12.1 and 12.5%. The grain used in Vanduzi district was free of insects, while the grain used in Sussundenga Sede and Rotanda had 3.7 individuals/kg and 3.0 individuals/kg respectively. In both districts where the *on-farm* trials were conducted, it was observed an increasing trend of the insect density for the grain held in polypropylene bags with over 270-fold increase in Vanduzi ($F_{3,35}$ = 265.8, P < 0.05) and over 60-fold increase in Sussundenga district ($F_{3,35}$ = 37.0, P < 0.05). For Vanduzi, the number of insects did not increase significantly for the grain stored in hermetic systems. In contrast, in Sussundenga a significant increase was observed for the grain stored in polyethylene drum ($F_{3,35}$ = 7.1, P < 0.05), showing the highest increase in Munhinga locality ($F_{3,5}$ = 44.4, P < 0.05) with 15-fold increase. In general, grain stored in SGB showed stability in the population of insects throughout the storage period (Table 1).

The grain used for *on-farm* trials had a slightly different level of damage for different sites. The grain used in Vanduzi district did not show any damage at the beginning of the trials, while the grain used in Sussundenga showed 0.7% of damage in Munhinga locality and 2.0% in Rotanda locality.

In Vanduzi district, the percentage of damaged grain in polypropylene bags showed an increasing trend ($F_{3,35}$ = 200.4, P < 0.05), achieving over 89% after 240 days of storage. On the other hand, the percentage of damaged grain increased up to 120 days of storage ($F_{2,53}$ = 38.9, P < 0.05) for the hermetic system. From 120 days onwards, the percentage of damaged grain was stable ($F_{1,35}$ = 1.91, P = 0.17) and remained below 4%, with no significant differences between the two containers. A

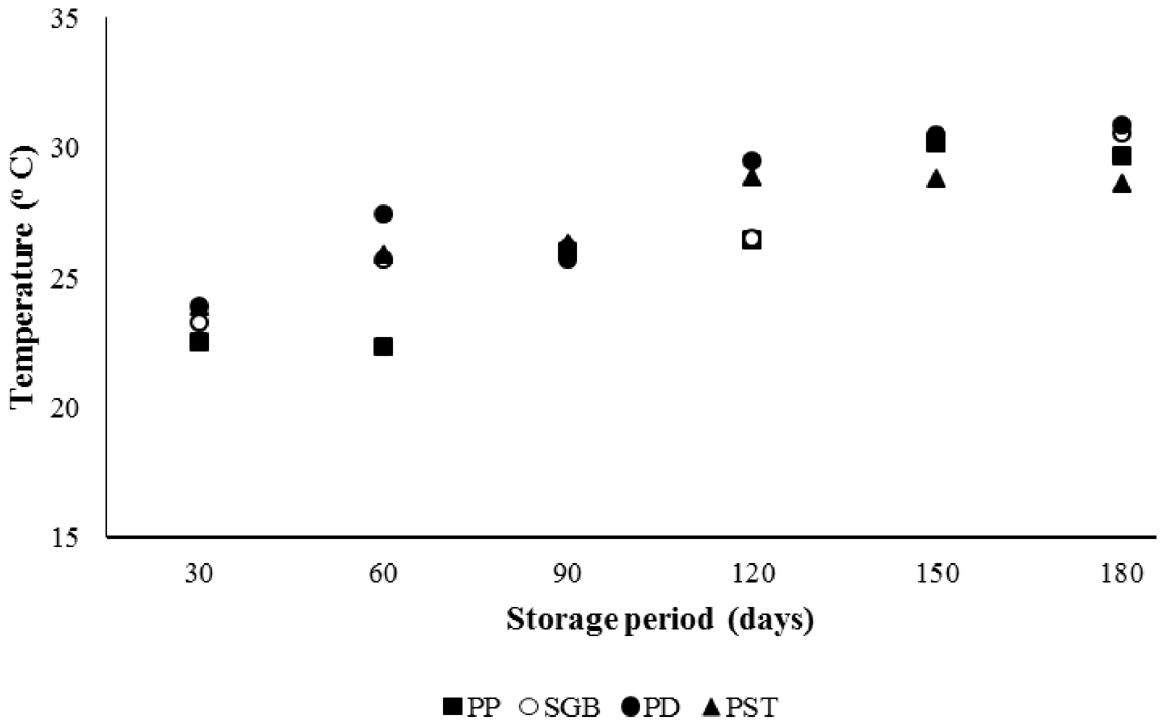

Figure 6. Variation in temperature in maize stored in different storage containers over 180 days. PP = Polypropylene bag; SGB = super grain bag; PD = polyethylene drum; PST = polyethylene silo tank.
Source: Author

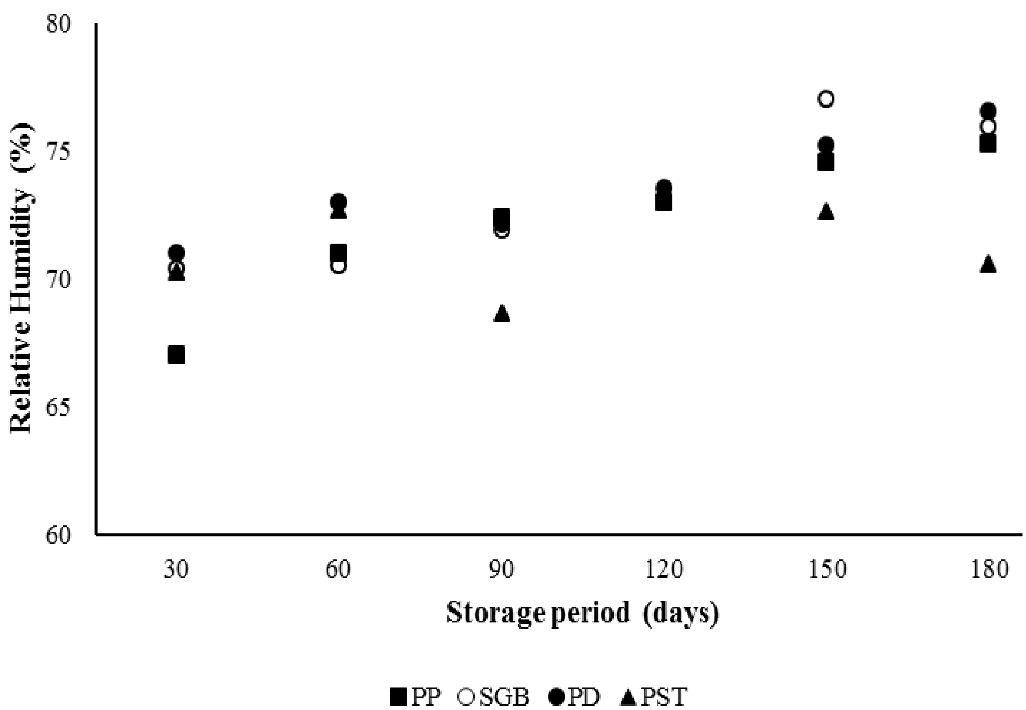

Figure 7. Variation in relative humidity in maize stored in different storage containers over 180 days. PP = Polypropylene bag; SGB = super grain bag; PD = polyethylene drum; PST = polyethylene silo tank.
Source: Author

Table 1. Mean insect density in different storage containers and the respective percentage abundance over 240 days of *on-farm* storage (mean ± SE).

District	Locality	Storage container	Insect density (insect/kg)			Damaged grain (%)		
			60 days	120 days	240 days	60 days	120 days	240 days
Vanduzi	Chitundo	PP	35.7 ± 5.9^{a}	100.3 ± 4.1^{b}	270.0 ± 13.5^{a}	14.3 ± 2.4^{a}	35.0 ± 5.2^{a}	76.7 ± 5.2^{a}
		SGB	0.0 ± 0.0^{e}	1.7 ± 0.3^{b}	1.7 ± 1.5^{c}	1.0 ± 0.5^{b}	2.0 ± 0.5^{b}	2.7 ± 0.7^{b}
		PD	7.0 ± 2.4^{bc}	2.0 ± 0.5^{b}	2.0 ± 0.8^{bc}	2.7 ± 0.3^{b}	3.0 ± 0.5^{b}	3.3 ± 1.2^{b}
	Belas	PP	34.3 ± 5.6^{a}	136.3 ± 23.4^{a}	$295.3\ 12.8^{a}$	19.3 ± 3.1^{a}	45.3 ± 6.2^{a}	80.3 ± 2.8^{a}
		SGB	3.7 ± 0.7^{da}	2.0 ± 0.5^{b}	1.0 ± 0.8^{c}	2.0 ± 0.5^{b}	2.7 ± 0.3^{b}	3.3 ± 1.0^{b}
		PD	6.3 ± 1.0^{c}	2.0 ± 0.5^{b}	3.0 ± 0.8^{b}	2.0 ± 0.5^{b}	3.0 ± 0.5^{b}	3.7 ± 1.4^{b}
	Selva	PP	40.3 ± 4.3^{a}	133.7 ± 14.6^{a}	284.3 ± 17.9^{a}	11.7 ± 1.8^{a}	31.3 ± 2.8^{a}	84.7 ± 3.7^{a}
		SGB	8.0 ± 1.2^{bc}	4.7 ± 0.7^{b}	2.7 ± 1.8^{bc}	1.0 ± 0.5^{b}	2.3 ± 0.3^{b}	3.3 ± 1.2^{b}
		PD	11.3 ± 0.7^{b}	3.0 ± 0.6^{b}	4.0 ± 1.9^{b}	3.0 ± 0.9^{b}	4.0 ± 0.9^{b}	6.0 ± 1.7^{b}
Sussundenga	Sussundenga Sede	PP	50.7 ± 5.6^{a}	75.0 ± 19.8^{b}	207.0 ± 13.8^{a}	12.0 ± 2.6^{a}	22.3 ± 1.9^{a}	66.7 ± 4.7^{a}
		SGB	0.7 ± 0.3^{a}	3.7 ± 1.0^{e}	4.3 ± 1.7^{d}	1.3 ± 0.3^{b}	3.3 ± 1.2^{c}	3.7 ± 1.2^{b}
		PD	6.3 ± 2.3^{c}	10.7 ± 0.7^{d}	11.7 ± 1.7^{cd}	2.7 ± 0.7^{b}	3.7 ± 0.7^{c}	5.3 ± 1.0^{b}
	Munhinga	PP	34.3 ± 5.4^{b}	51.3 ± 19.1^{c}	126.3 ± 1.8^{b}	8.7 ± 1.2^{a}	26.0 ± 3.3^{a}	69.3 ± 1.7^{a}
		SGB	0.0 ± 0.0^{a}	3.3 ± 1.5^{e}	5.3 ± 2.3^{d}	1.7 ± 0.5^{b}	1.0 ± 0.5^{c}	4.0 ± 1.4^{b}
		PD	0.0 ± 0.0^{a}	9.3 ± 0.7^{da}	15.0 ± 2.9^{c}	1.0 ± 0.5^{b}	4.0 ± 0.8^{c}	6.3 ± 2.4^{b}
	Rotanda	PP	52.7 ± 9.3^{a}	147.0 ± 21.6^{a}	185.7 ± 9.1^{a}	12.7 ± 2.2^{a}	19.0 ± 2.1^{a}	55.3 ± 10.4^{a}
		SGB	0.7 ± 0.3^{a}	4.3 ± 1.1^{e}	5.7 ± 0.7^{d}	1.3 ± 0.7^{b}	3.7 ± 0.5^{c}	4.7 ± 1.9^{b}
		PD	9.3 ± 1.2^{c}	7.0 ± 2.8^{d}	6.7 ± 2.7^{d}	3.0 ± 0.9^{b}	7.3 ± 1.4^{b}	9.3 ± 1.2^{b}

Means followed by different letters in column within the same district are significantly different ($p < 0.05$). PP = Polypropylene bag; SGB = super grain bag; PD = polyethylene drum.
Source: Author

similar trend was observed in Sussundenga, but with lower damage for grains stored in polypropylene ($F_{3,35}$ = 96.1, $P < 0.05$) bags with values below 70 % and no significant differences amongst the localities ($F_{2,35}$ = 0.71, P = 0.49). However, grain held in polyethylene drum showed the highest percentage of damage amongst the hermetic systems in Rotanda, with about a 5-fold increase compared to the initial value, and 2-fold over SGB.

Sensory analysis

After eight months of storage, no significant differences were observed in the acceptability level of the appearance of the grain stored in Super Grain Bags and polyethylene drums ($F_{1,189}$ = 2.7, P = 0.10), with over 75% of the panellist attributing a score equal or above 7 (grain of moderately good appearance) (Figure 8). In addition, none of the evaluators considered the grain stored in these containers as of bad appearance. On the other hand, the grain stored in the polypropylene bag had the lowest ($F_{3,379}$ = 209, $P < 0.05$) acceptability score, with only 20% of farmers considering the grain suitable for human consumption with the highest score being 6 (grain of slightly good appearance).

DISCUSSION

Naturally infested grain was used in the experiment, and the initial mean density of insects was about 26 individuals/kg of maize. The population of insects increased by 31-fold along the storage period in polypropylene bags without the insecticide Actellic®, while for the grain treated with the insecticide, a stable trend was observed in the first 120 days of storage, with only a 3-fold increase observed only after 180 days of storage when the insecticide was used. Polypropylene bags have been associated with high insect multiplication during storage, especially in tropical regions where the prevailing high temperatures favour a swift insect development (Mutambuki et al., 2019). Smallholder farmers in sub-Saharan Africa have widely used pesticide

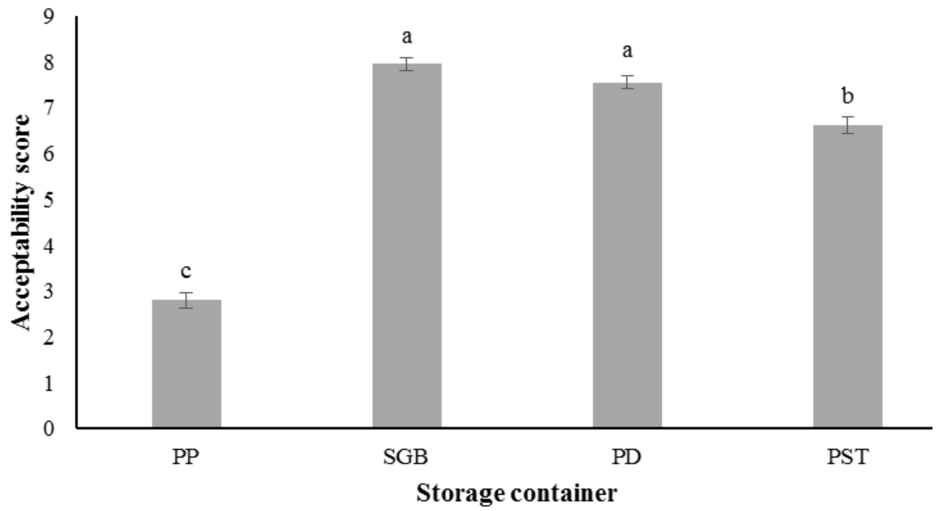

Figure 8. General appearance acceptability score (1, dislike very much, to 9, like very much) of grain stored in polypropylene bags (PP), Super Grain Bags (SGB), polyethylene drum (PD), and polyethylene silo tank (PST) (n = 95). Different letters show significant differences between the storage containers ($P < 0.05$).
Source: Author

as a strategy to contain insect multiplication. However, pesticides are effective for a limited time, posing the need for regular reapplication for extended grain storage, increasing the cost of pest control, environmental problems, and consumer exposure to health; Previous studies have also reported decreased actellic effectiveness against insects with time (Denloye et al., 2008; Nhamucho et al., 2012; Mubayiwa et al., 2021). For instance, De Groote et al. (2013) reported that polypropylene bags treated with actellic effectively controlled insect multiplication in maize and prevented grain damage only for four months.

The use of chemical-free techniques to control insect multiplication could fulfill the consumer increased demand for chemical-free products while preserving the environment. For this purpose, hermetic containers such as Super Grain Bags, polyethylene drum, and polyethylene silo tanks could be an alternative for prolonged grain storage. These storage containers showed a high performance against insect multiplication, which could be attributed to the environment created within the storage ecosystem. The control of insect multiplication using hermetic storage is a result of oxygen depletion and carbon dioxide accumulation inside the container due to the respiration process of insects, fungi, and grain (Aboagye et al., 2017). This study results on the efficiency of Super Grain Bags and polyethylene containers to control insect multiplication are consistent with previous reports (Likhayo et al., 2018; Baributsa et al., 2020; Covele et al., 2020; Tivana et al., 2021).

Super Grain Bag was the most effective in suppressing insect multiplication amongst the hermetic containers after 90 days of storage. All the containers were opened every 30 days for grain sampling, and the resealing of polyethylene silo tank and polyethylene drum may have affected the hermetic conditions. Nevertheless, the insect slow development resulted in low insect density, as also previously observed in metal silos by Likhayo et al. (2016), which present a similar inlet to the containers evaluated under this study.

The grain stored in polypropylene bags was highly damaged after 180 days of storage, with over 70% of the grain showing damaged due to insect attack. Super Grain Bags presented the lowest percentage of damaged grain, while no significant differences were observed between polyethylene silo tank, polyethylene drum and polypropylene bags with actellic. Results on the percentage of damaged grain are consistent with the dynamic of insects' population in the storage containers along the storage period. Grain damage by insects, evident by exit holes made by insects, causes weight loss and reduction of grain market price, which translates into economic losses to the farmers.

Super Grain Bag has been successfully used to extend the storage period of crop grains such as maize (Mlambo et al., 2017; Likhayo et al., 2018), rice (Covele et al., 2020), and cowpea (Baoua et al., 2013), preserving the grain quality for over six months with no significant damage due to insect attack. On the other hand, studies on polyethylene containers have been scanty. However, the use of these containers has shown promising results. Evaluating the performance of polyethylene drums to preserve cowpea grain, Tivana et al. (2021) demonstrated that grain stored in this container had half of the percentage of grain damaged by insects than that observed in cowpea after 180 days of storage. The polyethylene drum and polyethylene silo tank also showed positive results on rice grain, with only about 3% of damaged grain observed after 12 months of storage (Covele et al., 2020). During the same period, the damaged grain for rice stored in polypropylene bags was 2-fold higher. The present study is the first to show the performance of polyethylene containers in preserving maize grain on-station and under smallholder farmers' conditions. The varieties of grain used on-farm trials may be different considering that smallholder farmers usually use mix of grains from different sources as seed. Regardless of these variations in the grain quality, testing the storage systems performance under the environment where they are most likely to be used is necessary. Results from *on-farm* trials confirmed the effectiveness of hermetic systems to limit insect multiplication and minimize grain damage, and similar trend was observed in all localities where the trials were established.

Maize held in Super Grain Bag and polyethylene drum was highly accepted by the smallholder farmers, as demonstrated by sensory evaluation of the appearance of grain. Grain stored in polyethylene silo tank presented the lowest ranking score amongst the hermetic containers since it had the highest grain damage level. However, it was still ranked of moderately good quality.

On the other hand, maize grain from polypropylene bags was considered unfit for human consumption. The high acceptance of maize grain stored in hermetic systems reflects the low attack by insects, resulting in a reduced percentage of damaged grain in these containers, making the grain more appealing to the consumer. Studies in coffee beans have also reported a high performance of hermetic storage structures in maintaining the sensory qualities for at least 12 months of storage (Ribeiro et al., 2011; Borém et al., 2019).

Grain stored in polypropylene bags was rejected by the sensory evaluation panel, which represents potential economic losses for farmers after eight months of storage. To avoid these losses, smallholder farmers tend to sell their grain just after harvest at a lower price due to the high offer of the grain in the market. On the other hand, using hermetic containers such as Super Grain Bags and polyethylene drums would allow farmers to safely store their grain just after harvest and sell when the price market is favourable.

It has been reported from several studies that insects can perforate plastic lines from inside and outside the bag. Therefore, the plastic liners were emptied and inspected for perforations after the storage period, but no holes were observed. Super Grain Bags showed slightly better performance than other hermetic containers in all evaluated parameters. However, farmers need to consider the cost-benefit of the storage containers and that Super Grain Bags are used for a short time, and are more likely to be perforated by insects, which might pose a disadvantage for smallholder farmers. Moreover, the widespread availability of the Super Grain Bag in numerous countries in Sub-Saharan Africa (SSA) remains limited, and its relatively high cost presents a barrier to its affordability for smallholder farmers.

On the other hand, polyethylene silo tanks and polyethylene drums are widely available in several SSA countries, and are commonly used for water storage. These containers have the additional advantage of being resistant to rodent attacks and perforations caused by insects. Therefore, leveraging the existing availability and benefits of polyethylene silo tanks and drums can provide a viable solution for grain storage, addressing the limitations of the Super Grain Bag regarding availability.

Further, the manufacturer company indicates that, if carefully handled, the life span of polyethylene containers could be over 15 years. Therefore, both high-density polyethylene containers could be more suitable for smallholder farmers since they need to invest once, representing a long-term economic investment. Nevertheless, polyethylene drum and polyethylene silo tank may not be practical for storing a high amount of grain in milling companies, as they cannot be piled up, and the grain's withdrawal for processing may be labour-demanding and time-consuming. For this reason, for companies, the use of Super Grain Bag may prove the best option, provided that additional measures are considered to control rodents and insects in the warehouse environment.

For any storage systems used, it is essential to conduct periodic assessments of the grain quality throughout the storage period for early detection of an increase in insect activity or grain damage. Early identification of insect population increases will ensure the timely implementation of appropriate control methods.

Conclusion

Both *on-station* and *on-farm* trials showed that the Super Grain Bag, polyethylene drum, and polyethylene silo tank (*on-station*) effectively limited insect multiplication and minimized maize grain damage over six months of storage for *on-station* and eight months for *on-farm*. Moreover, the hermetic systems minimized weight loss over the storage period. On the other hand, the traditional polypropylene bags did not prevent the multiplication of insect pests and grain loss throughout the storage period. The present study suggests that the evaluated hermetic containers can be an alternative for smallholder farmers to preserve maize grain for at least six months without using pesticides, minimizing grain postharvest losses due to storage insect attacks. The extended storage period will allow farmers to improve their income since farmers can sell their grain when prices are favourable and not immediately after harvest when supply is high, and prices are typically lower. Super Grain Bag was slightly better than the high-density polyethylene containers in controlling insect multiplication.

There is a need to conduct a cost-benefit analysis to assess which of the evaluated containers bring more financial benefits to the farmers in the long term. Additionally, further studies to evaluate the performance of the hermetic containers under analysis against grain stored fungi and mycotoxin accumulation are necessary, especially for the high-density polyethylene containers, to ensure that the consumption of grain stored in these containers does not pose a health risk to the consumers due to exposure to mycotoxin.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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