# Comparative performance of five hermetic bag brands during on-farm smallholder cowpea (*Vigna unguiculata* L.Walp) storage

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## Abstract

Cowpea (*Vigna unguiculata* L. Walp) grain is an important source of protein for smallholder farmers in developing countries. However, cowpea grains are highly susceptible to bruchid attack, resulting in high quantitative and qualitative postharvest losses (PHLs). We evaluated the performance of five different hermetic bag brands for cowpea grain storage in two contrasting agro-ecological zones of Zimbabwe (Guruve and Mbire districts) for an 8-month storage period during the 2017/18 and 2018/19 storage seasons. The hermetic bag treatments evaluated included: GrainPro Super Grain bags (SGB) IVR™; PICS bags; AgroZ® Ordinary bags; AgroZ® Plus bags; ZeroFly® hermetic bags. These were compared to untreated grain in a polypropylene bag (negative control) and Actellic Gold Dust® (positive chemical control). All treatments were housed in farmers' stores and were subjected to natural insect infestation. Hermetic bag treatments were significantly superior ($p < 0.001$) to non-hermetic storage in limiting grain damage, weight loss and insect population development during storage. However, rodent control is recommended, as rodent attack rendered some hermetic bags less effective. Actellic Gold Dust® was as effective as the hermetic bags. *Callosobruchus rhodesianus* (Pic.) populations increased within eight weeks of storage commencement, causing high damage and losses in both quality and quantity, with highest losses recorded in the untreated control. Cowpea grain stored in Mbire district sustained significantly higher insect population and damage than Guruve district which is ascribed to differences in environmental conditions. The parasitic wasp, *Dinarmus basalis* (Rondani) was suppressed by Actellic Gold Dust® and all hermetic treatments. All the hermetic bag brands tested are recommended for smallholder farmer use in reducing PHLs while enhancing environmental and worker safety, and food and nutrition security.

**Keywords**: Hermetic storage; on-farm storage; synthetic pesticide; *Callosobruchus rhodesianus*; postharvest losses

## 1.0 Introduction

Cowpea (*Vigna unguiculata* L.Walp*)* is an important plant-based source of protein and grown in many smallholder farming systems across the world (Jackai and Asante, 2003). In Africa, cowpea is grown both as a subsistence food and a cash crop. Insect pests attack cowpea grains post-maturity in the field and during storage. In West and Central Africa, the most important cowpea pest is the bruchid *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae) (Murdock et al., 2012), while in southern Africa, *C. rhodesianus* is more common (Amevoin et al., 2005). Substantial quantitative and qualitative losses of cowpeas occur due to insects perforating the cowpea kernels, resulting in their reduced weight, market value, and germination potential (Giga and Smith, 1987). Storage insect damage can result in high qualitative and quantitative losses of 30-80% of cowpeas, equivalent to US$300 million per year for Africa (Golob et al., 1999). Consumers demand substantial price discounts when purchasing bruchid-damaged cowpeas (Mishili et al., 2007). High loss figures – such as up to 95% after three months farmer level storage (Kitch and Sibanda, 2001) – underscore the need for effective storage methods to reduce both quantitative and qualitative postharvest losses (PHLs) of cowpea.

Smallholder farmers in sub-Saharan Africa (SSA) typically use synthetic pesticides and locally available plant materials (Koul et al., 2008) to control pests and prolong shelf-life of stored grains (Mvumi and Stathers, 2003; Nyamadi and Maphosa, 2013). Despite the use of these various grain protectants, PHLs are still high (Golob et al., 1999), leading many smallholder farmers to sell their grains soon after harvest to avoid storage losses (Affognon et al., 2015). More effective storage methods are needed.

Hermetic storage bags – which provide pesticide-free, effective grain protection against storage insect pests (Murdock and Baoua, 2014; Aboagye et al., 2017) – are becoming increasingly important in SSA. A range of different hermetic storage bag brands are being marketed across SSA countries, including Purdue Improved Crop Storage (PICS) bags, GrainPro Super Grain bags (SGBs) IVR™, ZeroFly® hermetic storage bags and AgroZ® bags. Hermetic storage containers rely on the principle of oxygen depletion with a corresponding rise in carbon dioxide which occurs as a result of insects, mites, microorganisms on the grain respiring in airtight bags (Murdock et al., 2012; Murdock and Baoua, 2014; Silva et al., 2018). Low oxygen (hypoxia) leads to cessation of *C. maculatus* larval feeding activity, inactivity, stopping of population growth, desiccation and eventual death of eggs, larvae, and pupae (Murdock et al., 2012; Baoua et al., 2012; Baoua et al., 2013; Murdock and Baoua, 2014; Silva et al., 2018).

On-station efficacy comparisons of four hermetic bag brands were conducted in Zimbabwe using maize grain and no significant differences in efficacy were found (Chigoverah and Mvumi, 2018). However, on-farm comparisons of the different hermetic storage bags are required to provide evidence of their relative efficacy, and to drive experiential learning by stakeholders, thereby increasing chances of adoption of the technology by farmers and their service-providers. Long-term on-farm studies with farmer and stakeholder participation are scarce.

An on-farm study of cowpeas storage losses in Zimbabwe reported grain damage greater than 50% in untreated control and less than 10% when diatomaceous earth or Actellic Super Dust were applied, showing their effectiveness over a 40-week storage duration (Stathers et al., 2002). However, there is little reliable measured as opposed to estimated data on PHLs of cowpeas grain during storage, especially in southern Africa. In the current study, we evaluated the comparative efficacy of five hermetic bag brands in preventing insect damage to on-farm stored cowpea grain under smallholder management in two agro-climatically contrasting districts of Zimbabwe.

## 2.0 Materials and methods

### 2.1. Site description

Storage field trials were conducted in two agro-climatically contrasting districts Guruve (16° 38'59.99" S and 30°41' 59.99" E) and Mbire (20°43'60" S and 30°34'60" E) in Zimbabwe, during two grain storage seasons, 2017/18 and 2018/19. Zimbabwe is divided into five agro-ecological regions based on the amount of rainfall received, temperature and to a lesser extent the soil type. Region I receives the highest amounts of rainfall while region V denotes the most arid parts of the country. Guruve district is located in the natural agro-ecological region III, with annual rainfall of 650-800mm and mean annual temperature range of 18-35$^{o}$C, whereas Mbire district is in the drier agro-ecological region IV of Zimbabwe receiving annual rainfall below 450mm and with a mean annual temperature range of 32-42$^{o}$C (Mugandani et al., 2012). Guruve ward 6 and Mbire ward 6 were purposively selected in consultation with district stakeholders (Fig. 1).


**Figure 1**: Map of Zimbabwe showing study sites in Guruve and Mbire districts, Zimbabwe

## 2.2. Storage structures, grain preparation, treatments and storage

Four smallholder farmers with similar brick granaries and roofing materials were selected as Learning Centre representatives of the storage trials in each of the two wards in Guruve and Mbire districts, respectively. Learning centers comprised of neighboring smallholder farmers to the storage trials host, extension staff and University of Zimbabwe research team to engage in independent and self-directed learning on cowpea storage. The storage structures in Guruve district ward 6 were constructed from mud bricks, floors and walls plastered with cement and roofed using asbestos sheets, whilst in Mbire district ward 6, they were constructed from mud bricks, plastered with mortar and roofed using thatch grass.

The host farmers were selected based on their likelihood of wide-interactions with surrounding farmers in the community, ease of accessibility of their households by fellow farmers and service-providers, security of trial grain during storage, and availability of a suitable storage structure. To build local ownership of the trials, local farmers, community leadership, agricultural extension staff as well as the researchers participated in trial-setting and sampling.

A total of 1500 kg cowpea grain was procured locally in each season and mixed thoroughly to ensure baseline uniformity. Cowpeas (variety CBC 2) harvested in 2017 and 2018 growing seasons, were used for the 2017/18 and 2018/19 storage trials, respectively. Seven treatments (Table 1) were set up without any prior chemical treatment or fumigation of the cowpea grain, and with no artificial addition of insects.

The mixed cowpea grain was then sub-divided, on different plastic sheets, into 100 kg portions to enable 4 x 25 kg replicates per treatment to be set up in each ward. In the case of all the hermetic bags and the untreated control, the grain was loaded into the bags without any chemical treatment. Prior to placing the hermetic bag liners in polypropylene bags, they were tested for air tightness or leakage by filling the air to form a pouch before compressing with both hands. A hissing sound indicate that liner is perforated; thus, only liners without leakages were used.  After loading the grain, hermetic bags were pressed to squeeze out air and securely tied to ensure airtightness thus leading to a hermeticity. For the synthetic chemical (positive control), each 100 kg portion of cowpeas grain was thoroughly admixed with the product on plastic sheeting using a shovel before loading into 50 kg polypropylene bags. All the bags were then tightly closed by tying them securely using lengths of rubber strips. Each treatment replicate (25kg of cowpea grain), was raised on fire-burnt bricks to protect the grain from moisture ingress occurring from the floor. The trials were conducted for a 32-week storage period during both the 2017/18 and 2018/19 storage seasons.

**Table 1. Cowpeas storage treatments evaluated under smallholder farmer management in Guruve and Mbire districts, Zimbabwe**

| Category | Treatment/Trade Name | Description |
|---|---|---|
| Positive control (Registered synthetic pesticide) | Actellic Gold Dust® | A cocktail of pirimiphos-methyl 1.6% and thiamethoxam 0.36%; applied at 0.5 g/kg. |
| Hermetic storage technologies | Purdue Improved Crop Storage (PICS) bag | Two high-density polyethylene (HDPE) liners with 80 $\mu$m thickness fitted inside a third woven polypropylene bag. |
| | GrainPro Super Grain bag (SGB) IVR™ | Low-density polyethylene (LDPE) multi-layered single plastic liner with 78±2 $\mu$m thickness and oxygen permeability <3 cc/m$^2$ per day fitted inside a polypropylene bag. |
| | ZeroFly® hermetic storage bag | Insecticide-incorporated (deltamethrin applied at 3 mg/kg) polypropylene bags with hermetic HDPE liner inside with 65 $\mu$m thickness and oxygen permeability 2.5 cc/m$^2$ per day. |
| | AgroZ® Ordinary bag | A polypropylene outer bag and a multi-layer inner liner (co-extruded combining HDPE and Metallocene linear low density polyethylene - MLLDPE) with 90 $\mu$m thickness and oxygen permeability 2.2 cc/m$^2$ per day. |
| | AgroZ® Plus bag | A polypropylene outer bag and a multi-layer inner liner with 90 $\mu$m thickness and oxygen permeability <3 cc/m$^2$ per day. The multi-layer liner includes a central layer incorporating a repellent insecticide (alpha-cypermethrin) sandwiched between two barrier layers. |
| Negative control | Untreated | Untreated polypropylene bag |

### 2.3. Experimental design, trial-setting, sampling and sample analysis

Seven different grain storage treatments replicated four times were set up at each Learning Centre in a randomised complete block design (RCBD), with each of the four host households in each district forming a block. In the 2017/18 season, the storage trials were set-up in October 2017 and terminated in June 2018. In the 2018/19 season, the storage trials were set-in September 2018 and terminated in May 2019. Sampling of the cowpea grain was conducted at 8-weekly intervals. Samples of 1 kg were collected carefully using 1 m long multi-compartmented sampling spears to avoid puncturing the hermetic liners. The sampling spears were disinfected between collection of samples from different treatments to avoid cross contamination. Samples were analysed for insect grain damage, weight loss, insect-generated dust, adult insect counts (live and dead) and moisture content at the University of Zimbabwe laboratory in Harare.

### 2.4. Moisture content, insect-generated dust and insect population assessment

Samples were weighed first, then sieved to separate adult insects, insect-generated dust and grain before dividing them into sub-samples for grain damage analysis. Grain moisture was measured using a using a pre-calibrated moisture meter, GMK-303CF (GrainPro Inc., Subic Bay, Philippines). Grain was filled into the tester slot, crushed and moisture recorded. Dust generated from insect feeding was sieved through a 2 mm sieve (American Scientific Products, McGraw Park, Bloomington Illinois 60085) and the mass recorded. Dust content was expressed as a percentage of the total mass of the sample. Separation of insects and dust dust from whole grain was done using a 2 mm sieve as well. Counts of live and dead adult insects were done manually and recorded per species and converted to numbers per kilogram by simple proportion based on sample mass.

### 2.5. Grain damage and weight loss assessment

The 1 kg sample was divided into eight equal parts using a riffle divider. Three sub-samples representing three-eighths of the total sample were analysed for grain damage, manually separating the insect damaged from undamaged grains. Grains that had been perforated by insect pests were considered insect-damaged. Numbers of insect damaged (Nd) and undamaged (Nu) grains were used to calculate percentage grain damage. Grain weight loss percentage was calculated using the count and weigh loss assessment method (Boxall, 1986):

$$\text{Weight loss \%} = \frac{Nd*Wu-Wd*Nu}{(Nd+Nu)*Wu} \times 100$$

Where, Nd = number of damaged grains in a sample, *Nu* = number of undamaged grains in a sample, *Wu* = weight of undamaged grains in a sample and *Wd* = weight of damaged grains in a sample.

### 2.6. Assessment of insect perforation of hermetic bag liners

At the end of each storage season, the hermetic liners were analysed for damage. The number of holes were counted, and for each hole details of whether it was caused by rodent damage, insect pest damage, seam splitting or sampling spears used during sampling exercises, were recorded.

### 2.7. Data analysis

Data were tested for normality using Shapiro-Wilk test. The data on % insect grain damage, % weight loss, % moisture content and liners insect perforation holes' count met assumptions of normality and hence no transformations were required. Following high variability of data in preliminary tests, data for grain dust content and insect population/kg were transformed using cube root function (De Muth, 2014). One-way analysis of variance (ANOVA) with randomised blocks, adjusted for covariate (baseline sampling) in Genstat version 14, was applied to test for statistical significance on the mean percentage insect damaged grain, percentage weight loss, and percentage grain moisture content data at each sampling interval per ward. Tukey's protected test at 95% probability was used for treatment mean separation where statistical significance among the means were found. Cross comparison of treatment, season and sites was performed in Genstat 14 using Fishers protected LSD test at 95% confidence level. Data on insect perforation of bags were analysed using ANOVA to determine if there were any significant differences in beetle boring between different hermetic bag brands.

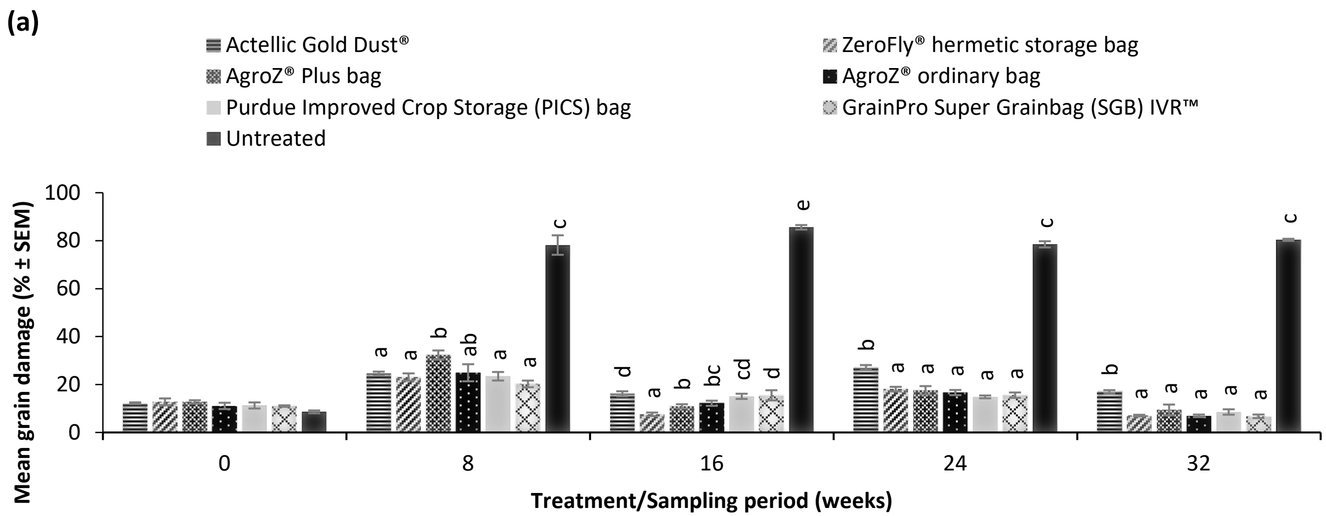
## 3.0 Results

### 3.1 Insect grain damage

In the 2017/18 storage season, insect grain damage levels in hermetic treatments and Actellic Gold Dust® were suppressed below 40 % in both Guruve and Mbire districts. In Guruve district, significant differences in insect grain damage between treatments were noted at 8 ($F_{6, 18} = 64.39$; $P < 0.001$), 16 ($F_{6, 18} = 840.47$; $P < 0.001$), 24 ($F_{6, 18} = 360.19$; $P < 0.001$) and 32 ($F_{6, 18} = 262.83$; $P < 0.001$) weeks. The highest damage was recorded in the untreated control followed by Actellic

Gold Dust® whilst no significant differences in terms of insect grain damage occurred among all the hermetic bag treatments. In Mbire district, significant differences in insect grain damage between treatments were recorded at 8 ($F_{6, 18} = 38.72$; $P < 0.001$), 16 ($F_{6, 18} = 45.27$; $P < 0.001$), 24 ($F_{6, 18} = 146.75$; $P < 0.001$) and 32 ($F_{6, 17} = 73.90$; $P < 0.001$) weeks. The highest damage levels were recorded in the untreated control, AgroZ® Plus bags and Actellic Gold Dust® respectively (Fig. 2). In Mbire, at the end of 32 weeks' storage, the hermetic bags, ZeroFly® hermetic storage bags, AgroZ® Ordinary bags, PICS, SGBs had the lowest significant damage, whereas grain stored in AgroZ® Plus bags had significantly higher damage. In Guruve, no significant differences between the different hermetic bag brands occurred throughout the 32 weeks' storage period.

Insect grain damage levels in the 2018/19 season were lower than in the 2017/18 storage season. In Guruve district, the initial damage level was below 5 % and it remained below 5 % for the 32 weeks of storage in all treatments. Significant differences in insect grain damage levels between treatments were, however, noted at 8 weeks ($F_{6, 18} = 2.95$; $P = 0.035$) of storage. Whilst all the hermetic bag treatments maintained insect damage levels below 2 %, damage exceeded 2% in the Actellic Gold Dust® and the untreated control (Fig. 3). In Mbire district, the trend was different. Initial damage level was between 3 and 4 %, and this level was maintained in the Actellic Gold Dust® and PICS bags treatments throughout the 32-week storage period. In the SGBs, AgroZ® Ordinary bags and AgroZ® Plus bags samples averaged 5 to 7 % damage levels at the end of the season, whilst grain stored in the ZeroFly® hermetic storage bags recorded up to 20 % damage (Fig. 3). However, grain damage exceeded 70 % in the untreated control. Grain damage levels were significantly different between treatments at 8 ($F_{6, 18} = 30.48$; $P < 0.001$), 16 ($F_{6, 18} = 304.53$; $P < 0.001$), 24 ($F_{6, 18} = 192.83$; $P < 0.001$) and 32 ($F_{6, 18} = 68.58$; $P < 0.001$) weeks of storage.


(a)
Actellic Gold Dust®
ZeroFly® hermetic storage bag
AgroZ® Plus bag
AgroZ® ordinary bag
Purdue Improved Crop Storage (PICS) bag
GrainPro Super Grainbag (SGB) IVR™
Untreated
Mean grain damage (% ± SEM)
0
20
40
60
80
100
0
8
16
24
32
Treatment/Sampling period (weeks)
a a b ab a a c
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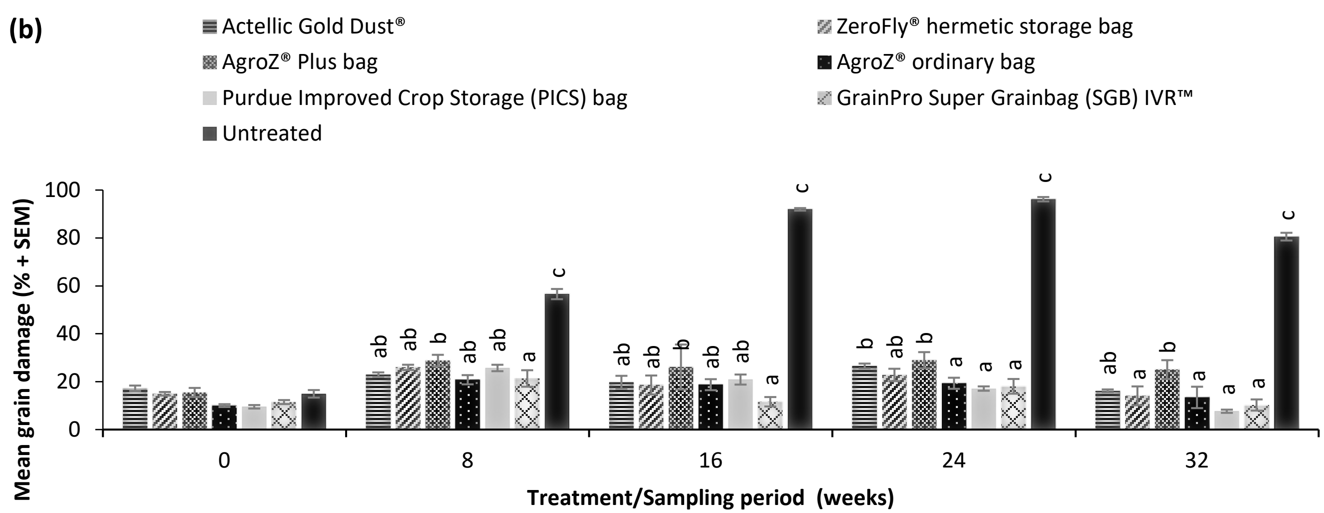
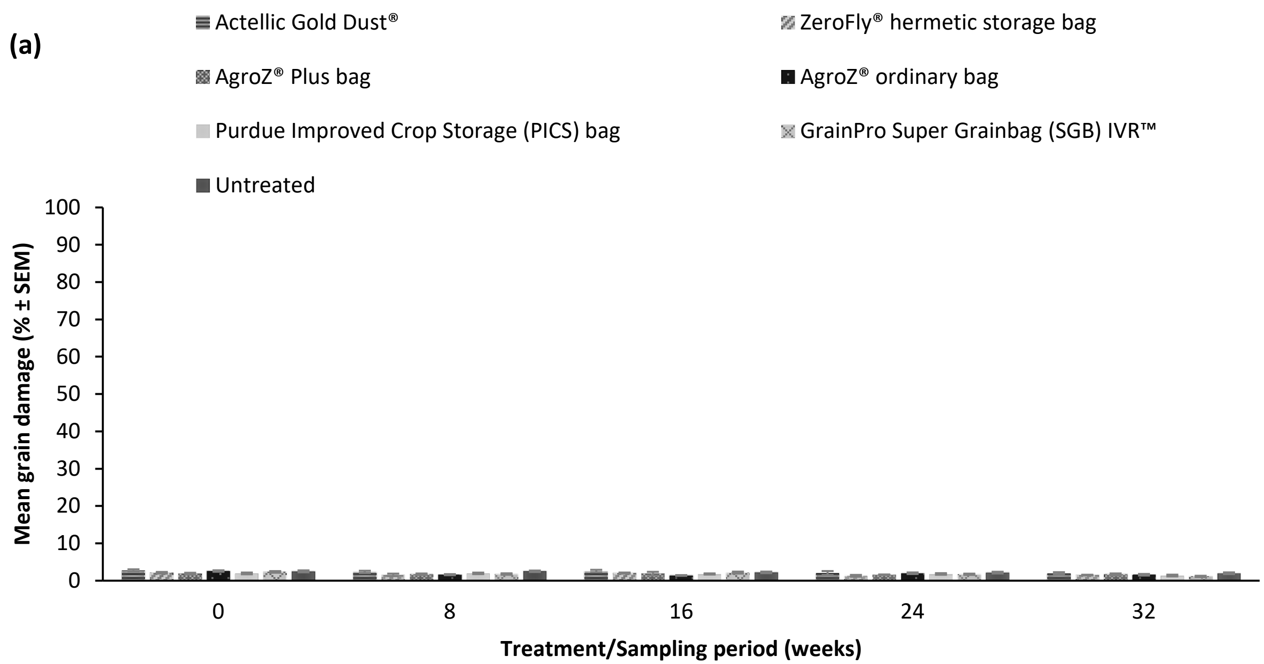

(b)
Actellic Gold Dust®
ZeroFly® hermetic storage bag
AgroZ® Plus bag
AgroZ® ordinary bag
Purdue Improved Crop Storage (PICS) bag
GrainPro Super Grainbag (SGB) IVR™
Untreated
Mean grain damage (% + SEM)
0
20
40
60
80
100
0
8
16
24
32
Treatment/Sampling period (weeks)
ab ab b ab ab a c
ab ab b ab ab a c
b ab b a a a c
ab a b a a a c

**Figure 2: Mean percentage grain damage (±SEM) in cowpea stored on-farm using different treatments during a 32-week period during the 2017/18 storage season in (a) Guruve and (b) Mbire districts (n=4).** ***The same letters within a sampling period denote no significant differences among the treatments*****.**



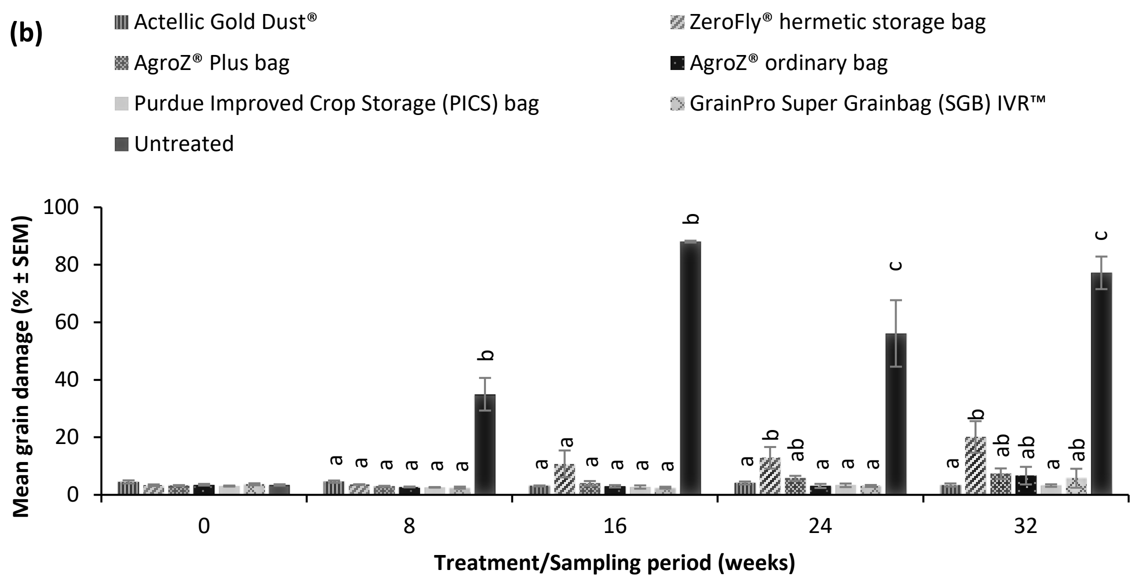



**Figure 3: Mean percentage grain damage (±SEM) in cowpea stored on-farm using different treatments during a 32-week period during the 2018/19 storage season in (a) Guruve and (b) Mbire districts (n=4).** ***The same letters within a sampling period denote no significant differences among the treatments*.**

### 3.2 Grain weight loss

In the 2017/18 season in both Guruve and Mbire districts, grain damage levels (Fig. 2) corresponded to the weight loss (Table 2) with the most damaged treatments recording the highest weight loss. The untreated control cowpea grain recorded the highest weight loss (>40 %) after 32 weeks' storage, with higher weight loss occurring in Mbire than Guruve. Significant difference in weight loss in both districts were recorded at 8, 16, 24 and 32 weeks ($P < 0.001$). The hermetic bags kept grain weight loss was low (<5 %) throughout the 32 weeks' storage period in both districts despite rodent and insect perforations of some of the hermetic bags. Grain weight loss in the Actellic Gold Dust® treatment in both districts, doubled during the storage period to around 8 %.

The initial weight loss in the 2018/19 season was lower than in the 2017/18 season. In Guruve district, it remained below 1 % and did not differ significantly between treatments throughout the 32 weeks of storage. Similarly, in Mbire district, weight loss remained below 1 % throughout the trial except in the untreated control where up to 20 % weight loss was recorded. Weight loss in the untreated control increased with storage duration, and was significantly higher than in the other treatments at 8 ($F_{6, 18} = 7.53$; $P < 0.001$), 16 ($F_{6, 18} = 54.04$; $P < 0.001$), 24 ($F_{6, 18} = 24.96$; $P < 0.001$) and 32 ($F_{6, 18} = 24.42$; $P < 0.001$) weeks of storage.

### 3.3 Proportion of insect-generated dust in the grain

The amount of dust generated due to insect feeding in the 2017/18 season was less than 1.5 % of the grain weight in all treatments in both districts. However, it was significantly higher in the untreated control than the other treatments resulting in significant differences at 8 ($F_{6, 18} = 39.92$;

$P < 0.001$), 16 ($F_{6, 18} = 49.02$; $P < 0.001$), 24 ($F_{6, 18} = 20.55$; $P < 0.001$) and 32 ($F_{6, 18} = 30.81$; $P < 0.001$) weeks storage (Table 3). In Mbire, the insect-generated dust in grain was significantly higher in the untreated control than in the other treatments at 8 ($F_{6, 18} = 33.91$; $P < 0.001$), 16 ($F_{6, 18} = 9.32$; $P < 0.001$), 24 ($F_{6, 18} = 7.98$; $P < 0.001$) and 32 ($F_{6, 18} = 26.05$; $P < 0.001$) weeks storage (Table 3).

Similarly, in the 2018/19 season, less than 1 % dust was recorded in all treatments across the two districts throughout the 32 weeks of storage. In Guruve district, no significant differences between treatments occurred, while in Mbire, significant differences between treatments occurred at 8, 16, 24 and 32 weeks of storage due to a gradual increase in dust in the untreated control (Table 4).

**3.4 Insect pest spectra and natural enemies in stored cowpeas**

The two major insects recorded from the stored cowpea were the bruchid, *C. rhodesianus* and *Dinarmus basalis* (Rondani) (Hymenoptera: Pteromalidae) parasitic wasps. In the 2017/18 season in Guruve, Actellic gold dust® and all the hermetic treatments kept *C. rhodesianus* populations below 400/kg (Fig. 4). By contrast, in the untreated control bruchid numbers increased rapidly between 0 and 8 weeks' storage to 921 insects/ kg rising to 1438/kg by week 32. Total numbers of insects per kg were significantly different between treatments at 8 ($F_{6, 18} = 40.28$; $P < 0.001$), 16 ($F_{6, 18} = 42.75$; $P < 0.001$), 24 ($F_{6, 18} = 74.28$; $P < 0.001$) and 32 ($F_{6, 18} = 51.63$; $P < 0.001$) weeks of storage.

**Table 2: Mean percentage weight loss (±SEM) in cowpea stored on-farm using different treatments during a 32-week period during the 2017/18 storage season in (a) Guruve and (b) Mbire districts (n=4).**

| Treatments | Sampling period (weeks) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Guruve district | | | | | Mbire district | | | | |
| | 0 | 8 | 16 | 24 | 32 | 0 | 8 | 16 | 24 | 32 |
| Actellic Gold Dust® | 1.1±0.88 | 2.8±0.38a | 2.6±0.42a | 4.2±1.09a | 4.2±0.44b | 1.8±0.17 | 2.7±0.23a | 2.3±0.24a | 3.6±0.59a | 3.6±0.52a |
| ZeroFly® hermetic storage bag | 1.3±0.73 | 3.1±1.51a | 3.1±0.41a | 3.5±0.54a | 3.2±0.26ab | 1.0±0.62 | 1.0±0.21a | 1.1±0.56a | 1.6±0.53a | 1.2±0.17a |
| AgroZ® Plus bag | 1.6±0.21 | 1.5±0.46a | 1.3±0.40a | 1.8±0.52a | 2.2±0.65ab | 1.3±0.89 | 1.2±1.47a | 1.8±0.42a | 1.8±0.50a | 1.8±0.62a |
| AgroZ® Ordinary bag | 1.3±0.50 | 2.3±0.79a | 2.4±0.89a | 2.4±0.39a | 2.3±0.38ab | 1.0±0.18 | 1.1±0.18a | 1.1±0.49a | 1.4±0.36a | 2.0±0.74a |
| Purdue Improved Crop Storage (PICS) bag | 1.3±0.05 | 1.7±0.22a | 1.1±0.29a | 1.23±0.94a | 1.6±0.66a | 1.5±0.78 | 1.3±0.71a | 1.3±0.21a | 1.7±0.22a | 1.5±0.22a |
| GrainPro Super Grain bag (SGB) IVR™ | 1.5±0.53 | 1.6±0.72a | 2.0±0.35a | 1.73±0.48a | 1.2±0.36a | 1.2±0.33 | 1.2±0.32a | 1.6±0.85a | 1.6±0.17a | 2.0±0.98a |
| Untreated control | 1.3±0.36 | 12.2±2.05b | 20.9±1.05b | 43.4±1.11b | 44.3±0.67c | 1.1±0.34 | 13.1±1.20b | 18.6±5.14b | 34.0±1.04b | 49.7±2.63b |
| P value | 0.997 | < 0.001 | < 0.001 | < 0.001 | < 0.001 | 0.711 | < 0.001 | < 0.001 | < 0.001 | < 0.001 |
| CV (%) | 23.0 | 23.9 | 24.5 | 19.1 | 12.3 | 23.9 | 30.3 | 30.7 | 18.1 | 28.6 |

Figures presented are the averages of each treatment. Means within a column are compared and separated using Tukey's test at p<0.05 and different letters indicate significant differences.

**Table 3: Mean percentage insect-generated dust (±SEM) in cowpea stored on-farm using different treatments during a 32-week period in Guruve and Mbire districts, during the 2017/18 storage season (n=4)**

| Treatments | Sampling period (weeks) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Guruve district | | | | | Mbire district | | | | |
| | 0 | 8 | 16 | 24 | 32 | 0 | 8 | 16 | 24 | 32 |
| Actellic Gold Dust® | 0.3±0.27 | 0.2±0.22b | 0.1±0.12c | 0.1±0.01a | 0.1±0.14b | 0.4±0.41 | 0.2±0.23b | 0.1±0.15a | 0.1±0.08a | 0.1±0.07a |
| ZeroFly® hermetic storage bag | 0.8±1.22 | 0.1±0.25ab | 0.1±0.24bc | 0.1±0.02a | 0.1±0.02ab | 0.5±0.60 | 0.1±0.10ab | 0.1±0.21a | 0.1±0.37a | 0.1±0.03a |
| AgroZ® Plus bag | 0.3±0.54 | 0.1±0.08a | 0.04±0.08a | 0.03±0.01a | 0.03±0.07a | 0.6±0.95 | 0.1±0.20a | 0.1±0.27a | 0.1±0.16a | 0.1±0.18a |
| AgroZ® Ordinary bag | 0.3±0.25 | 0.1±0.11ab | 0.1±0.07c | 0.1±0.01a | 0.1±0.05ab | 0.5±0.99 | 0.1±0.20ab | 0.1±0.24a | 0.1±0.12a | 0.1±0.09a |
| Purdue Improved Crop Storage (PICS) bag | 0.2±0.09 | 0.1±0.07a | 0.1±0.07ab | 0.03±0.01a | 0.03±0.01a | 0.3±0.19 | 0.1±0.07a | 0.1±0.02a | 0.1±0.07a | 0.03±0.04a |
| GrainPro Super Grain bag (SGB) IVR™ | 0.3±0.44 | 0.1±0.21ab | 0.1±0.16c | 0.1±0.02a | 0.1±0.05ab | 0.4±0.29 | 0.1±0.06a | 0.1±0.13a | 0.1±0.15a | 0.1±0.18a |
| Untreated control | 0.3±0.65 | 0.6±0.06c | 0.4±0.21d | 0.3±0.05b | 0.5±0.37c | 0.4±0.27 | 0.5±0.28c | 0.9±1.58b | 1.3±1.50b | 1.4±0.66b |
| P value | 0.07 | < 0.001 | < 0.001 | < 0.001 | < 0.001 | 0.635 | < 0.001 | < 0.001 | < 0.001 | < 0.001 |
| CV (%) | 12.5 | 11.3 | 12.8 | 18.8 | 12.5 | 12.9 | 14.9 | 23.8 | 26.2 | 16.2 |

Figures presented are the original averages of each treatment. Data analysis was on transformed data using the cube root function. Means within a column are compared and separated using Tukey's test at $p<0.05$ and different letters indicate significant differences.

**Table 4: Mean percentage insect-generated dust (±SEM) in cowpea stored on-farm using different treatments during a 32-week period during the 2018/19 storage season in Guruve and Mbire districts (n=4)**

| Treatments | Sampling period (weeks) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Guruve district | | | | | Mbire district | | | | |
| | 0 | 8 | 16 | 24 | 32 | 0 | 8 | 16 | 24 | 32 |
| Actellic Gold Dust® | 0.1±0.01 | 0.1±0.01a | 0.1±0.12a | 0.1±0.04a | 0.1±0.02a | 0.1±0.01 | 0.1±0.01a | 0.1±0.01a | 0.1±0.01a | 0.1±0.01a |
| ZeroFly® hermetic storage bag | 0.1±0.01 | 0.1±0.01a | 0.1±0.24a | 0.1±0.01a | 0.1±0.01a | 0.1±0.02 | 0.1±0.01a | 0.1±0.02a | 0.2±0.03b | 0.2±0.02b |
| AgroZ® Plus bag | 0.1±0.01 | 0.1±0.02a | 0.1±0.08a | 0.1±0.01a | 0.1±0.01a | 0.1±0.01 | 0.1±0.02a | 0.1±0.01a | 0.1±0.08a | 0.1±0.01a |
| AgroZ® Ordinary bag | 0.1±0.01 | 0.1±0.01a | 0.1±0.07a | 0.1±0.01a | 0.1±0.03a | 0.1±0.02 | 0.1±0.01a | 0.1±0.02a | 0.2±0.01b | 0.1±0.03a |
| Purdue Improved Crop Storage (PICS) bag | 0.1±0.02 | 0.1±0.01a | 0.1±0.07a | 0.1±0.01a | 0.1±0.01a | 0.1±0.01 | 0.1±0.01a | 0.1±0.01a | 0.1±0.01a | 0.1±0.01a |
| GrainPro Super Grain bag (SGB) IVR™ | 0.1±0.02 | 0.1±0.02a | 0.1±0.16a | 0.1±0.02a | 0.1±0.02a | 0.1±0.01 | 0.1±0.01a | 0.1±0.01a | 0.1±0.02a | 0.1±0.02a |
| Untreated control | 0.1±0.01 | 0.3±0.01b | 0.4±0.21b | 0.3±0.02b | 0.4±0.37b | 0.1±0.01 | 0.3±0.01b | 0.7±0.04b | 1.1±0.07c | 0.8±0.07c |
| P value | 0.08 | < 0.001 | < 0.001 | < 0.001 | < 0.001 | 0.74 | < 0.001 | < 0.001 | < 0.001 | < 0.001 |
| CV % | 14.0 | 13.3 | 22.8 | 16.5 | 14.4 | 11.3 | 15.0 | 13.7 | 24.4 | 13.7 |

Figures presented are the original averages of each treatment. Data analysis was on transformed data using the cube root function. Means within a column are compared and separated using Tukey's test at $p<0.05$ and different letters indicate significant differences.

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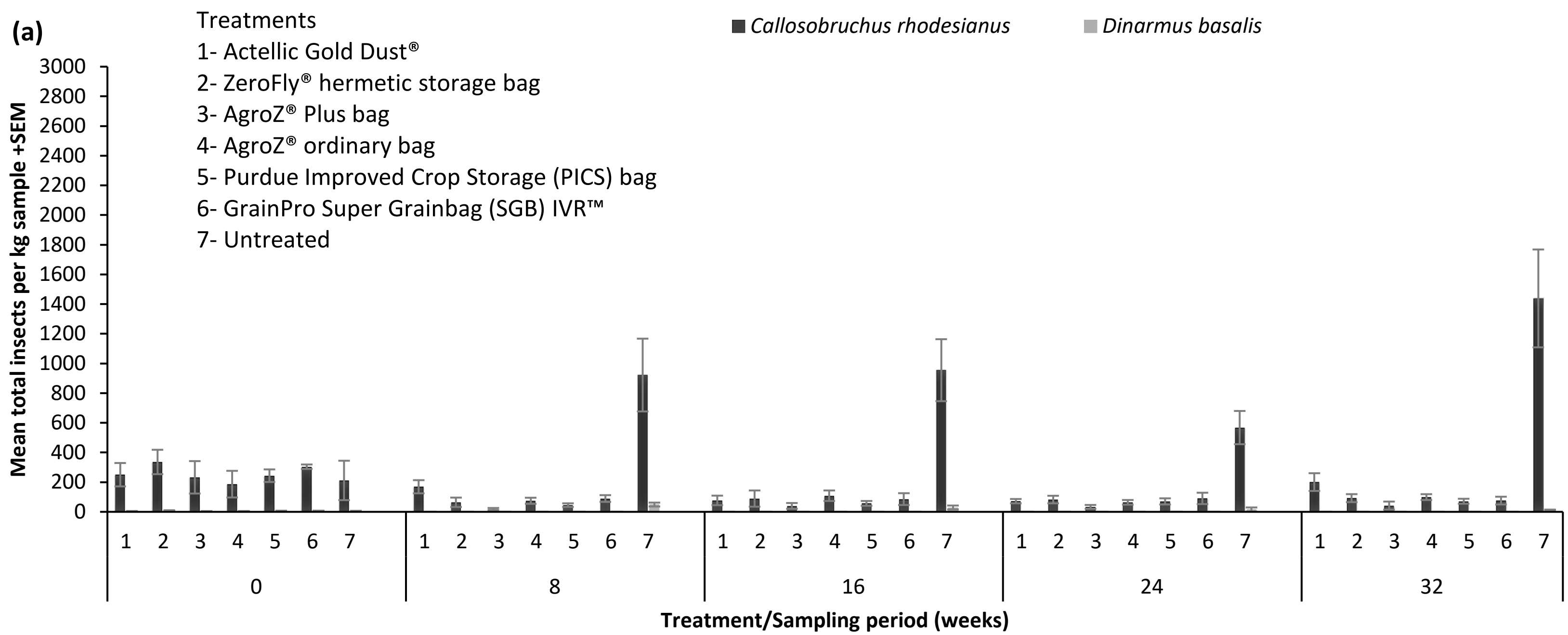

(a)
Treatments
1- Actellic Gold Dust®
2- ZeroFly® hermetic storage bag
3- AgroZ® Plus bag
4- AgroZ® ordinary bag
5- Purdue Improved Crop Storage (PICS) bag
6- GrainPro Super Grainbag (SGB) IVR™
7- Untreated
Callosobruchus rhodesianus
Dinarmus basalis
Mean total insects per kg sample +SEM
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1 2 3 4 5 6 7
0
8
16
24
32
Treatment/Sampling period (weeks)

295

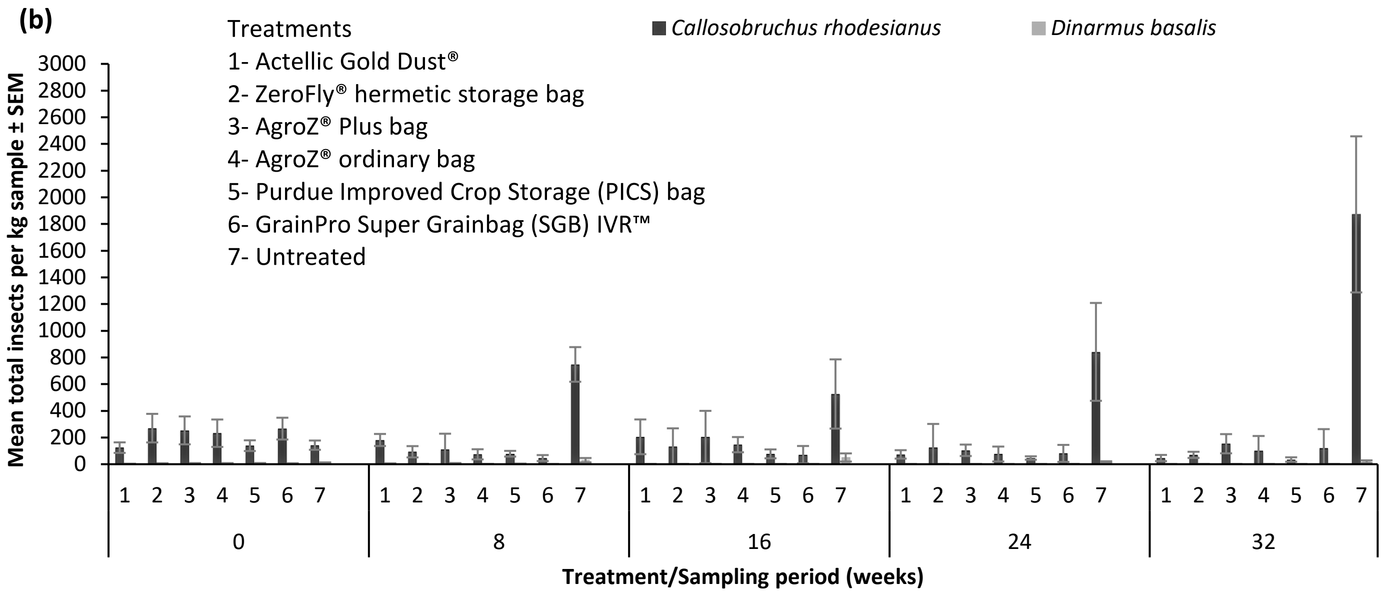
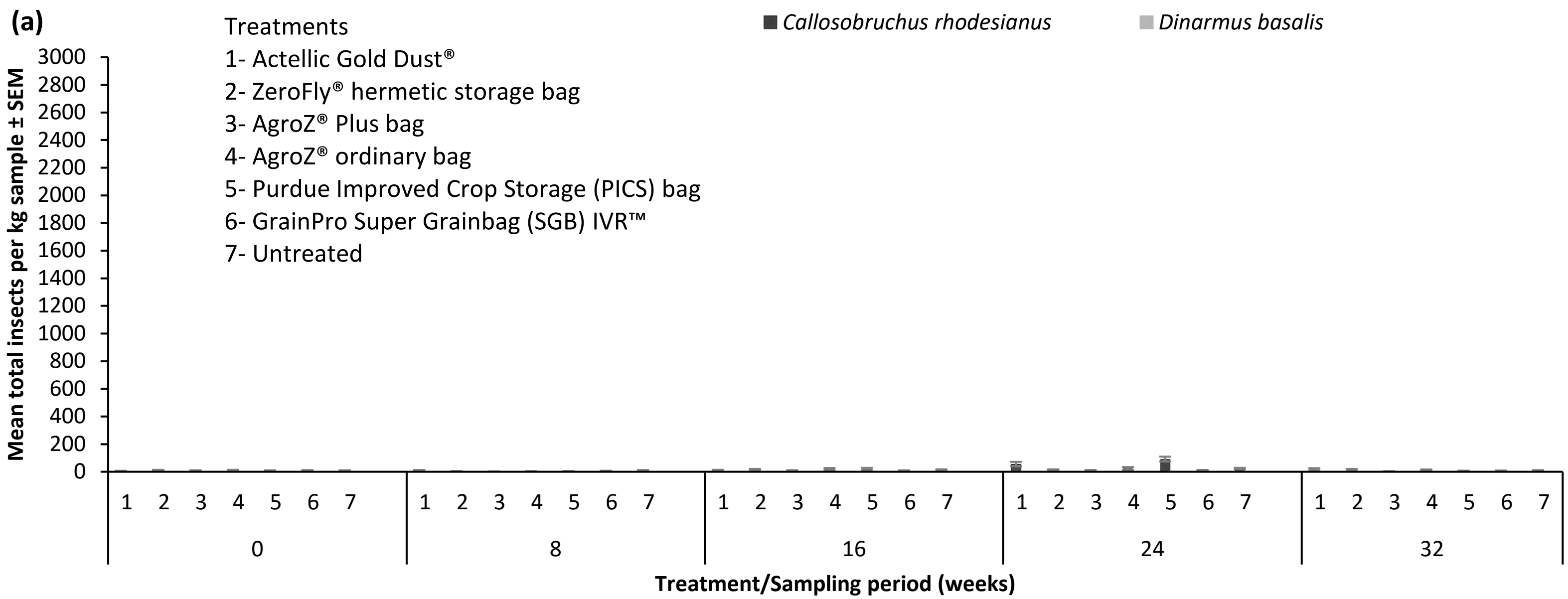
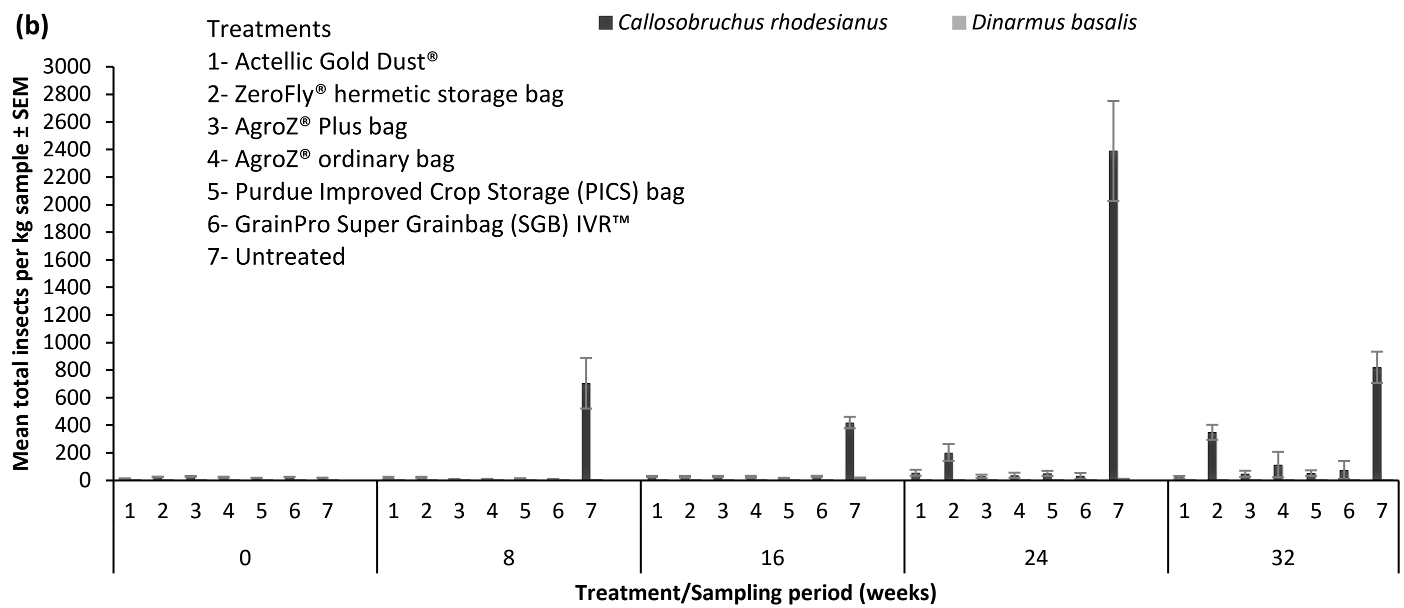



**Figure 4: Mean total adult insects per kg (± SEM) recorded in cowpea stored on-farm using different treatments during a 32-week period during the 2017/18 storage season in (a) Guruve and (b) Mbire district (n=4).**


(a)
Treatments
1- Actellic Gold Dust®
2- ZeroFly® hermetic storage bag
3- AgroZ® Plus bag
4- AgroZ® ordinary bag
5- Purdue Improved Crop Storage (PICS) bag
6- GrainPro Super Grainbag (SGB) IVR™
7- Untreated
Callosobruchus rhodesianus
Dinarmus basalis
Mean total insects per kg sample ± SEM
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1 2 3 4 5 6 7
0
8
16
24
32
Treatment/Sampling period (weeks)




301

302 **Figure 5: Total adult insects per kg (± SEM) recorded in cowpea stored on-farm using different treatments during a 32-week**
303 **period during the 2018/19 storage season in (a) Guruve and (b) Mbire districts (n=4).**

Similarly, in Mbire, insect populations were suppressed in the Actellic Gold Dust® and all hermetic treatments. Only in the untreated control did insect populations substantially increase, peaking at close to 2000 insects per kilogram at 32 weeks of storage (Fig. 4). Significant differences between treatments were recorded at 8 ($F_{6, 18} = 34.91$; $P < 0.001$), 16 ($F_{6, 18} = 3.31$; $P = 0.022$), 24 ($F_{6, 18} = 20.48$; $P < 0.001$) and 32 ($F_{6, 18} = 10.32$; $P < 0.001$) weeks of storage. The highest insect populations were recorded in the untreated control and at week 32 (1872 total insects per kg). For the other sampling periods, there were no significant differences between all hermetic treatments and Actellic Gold Dust®.

The total insect populations for Guruve were much lower in the 2018/19 season compared to the previous 2017/18 season. The highest level recorded was approximately 91 and 56 insects per kg recorded in PICS bags and Actellic Gold Dust®, respectively at 24 weeks' storage. In the other treatments, including the untreated control, insect populations were suppressed at/or below 20 insects per kilogram of grain (Fig. 5). Differences in insect population between treatments were significant at 8 ($F_{6, 17} = 4.07$; $P = 0.010$) and 24 ($F_{6, 17} = 9.77$; $P < 0.001$) weeks of storage. At week 8, insect populations in the untreated control and Actellic Gold Dust® were significantly higher than in the other treatments, and by week 24, insect populations were significantly higher in the Actellic Gold Dust® and PICS bags (Fig. 5).

In Mbire district, 2018/19 season, insect populations were suppressed in the Actellic Gold Dust® and all the hermetic treatments except for the ZeroFly® hermetic storage bags, storage which recorded between 200 and 300 insects/kg at 24 and 32 weeks, respectively. In the untreated control, however, insect populations fluctuated throughout the season. A few *D. basalis* parasitic wasps (<16 per kg) were also recorded in the untreated control (Fig. 6). Significant differences in insect populations between treatments occurred at 8 ($F_{6, 18} = 14.47$; $P < 0.001$), 16 ($F_{6, 18} = 104.10$; $P <$

0.001), 24 ($F_{6, 17}$ = 73.16; P < 0.001) and 32 ($F_{6, 18}$ = 18.80; P < 0.001) weeks storage. At weeks 8, 16 and 24, the untreated control had higher insect populations than the rest of the treatments whilst at week 32, it was the untreated control followed by ZeroFly® hermetic storage bags. The rest of the treatments suppressed the pest population.

**3.5 Grain moisture content**

Grain moisture content was low at trial setting, with a mean of 7.7% in the 2017/18 storage season. Grain moisture content increased in all treatments. However, it increased at different rates in different treatments and was higher in the untreated control and Actellic Gold Dust® treatments than the hermetic treatments. These significant differences in grain moisture content between treatments occurred at 16 ($F_{6, 18}$ = 85.64; P < 0.001), 24 ($F_{6, 18}$ = 59.47; P < 0.001) and at 32 ($F_{6, 18}$ = 27.05; P < 0.001) weeks of storage (Table 5). In Mbire district, differences in grain moisture content between treatments were only significant at 16 ($F_{6, 18}$ = 2.81; P = 0.041) and 32 ($F_{6, 18}$ = 3.63; P = 0.017) weeks storage. At 16 weeks, grain moisture content was highest in the untreated control grain, while at 32 weeks it was highest in the AgroZ® Plus bags treatment grain (Table 5). The average grain moisture content for Guruve district, 2018/19 season was 8.7% at trial setting, and increased to between 9 and 10 % in the hermetic treatments, and up to 11 % in the Actellic Gold Dust® and untreated control grain during the 32 weeks of storage. Grain moisture content was significantly different between treatments at 8 ($F_{6, 18}$ = 3.44; P = 0.019), 16 ($F_{6, 18}$ = 12.94; P < 0.001); 24 ($F_{6, 18}$ = 21.85; P < 0.001) and 32 ($F_{6, 18}$ = 47.49; P < 0.001) weeks of storage. In Mbire district, grain moisture content was 9.1 % at trial setting, and then fluctuated increasing to week 8 and then declining between week 16 and 32. Significant differences in grain moisture content between treatments only occurred at week 16 ($F_{6, 18}$ = 4.73; P = 0.005) (Table 6).

**Table 5: Mean percentage moisture content (±SEM) in cowpea stored on-farm using different treatments during a 32-week period during the 2017/18 storage season in Guruve and Mbire districts (n=4).**

| **Treatment** | **Sampling period (weeks)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Guruve district** | | | | | **Mbire district** | | | | |
| | **0** | **8** | **16** | **24** | **32** | **0** | **8** | **16** | **24** | **32** |
| Actellic Gold Dust® | 7.7±0.20 | 9.4±0.38 | 10.5±0.19b | 11.9±0.38b | 10.7±0.26c | 7.8±0.26 | 8.4±0.13 | 9.2±0.59bc | 9.5±0.39 | 9.9±0.18ab |
| ZeroFly® hermetic storage bag | 7.6±0.21 | 8.4±0.09 | 7.7±0.15a | 8.9±0.10a | 9.2±0.21ab | 7.9±0.37 | 8.6±0.22 | 7.9±0.31b | 8.9±0.10 | 8.9±0.18a |
| AgroZ® Plus bag | 7.7±0.24 | 8.7±0.34 | 7.5±0.17a | 8.7±0.31a | 9.4±0.24b | 7.7±0.27 | 8.6±0.18 | 8.7±0.66abc | 10.2±0.50 | 11.4±0.71c |
| AgroZ® Ordinary bag | 7.6±0.14 | 8.4±0.07 | 7.4±0.04a | 8.8±0.09a | 8.8±0.14a | 7.7±0.25 | 8.5±0.13 | 8.7±0.42abc | 8.3±0.56 | 10.2±0.89abc |
| Purdue Improved Crop Storage (PICS) bag | 7.8±0.13 | 8.5±0.09 | 7.6±0.08a | 8.4±0.06a | 9.0±0.13ab | 7.8±0.02 | 7.5±1.04 | 7.7±0.17a | 8.3±0.44 | 8.9±0.11ab |
| GrainPro Super Grain bag (SGBs) IVR™ | 7.8±0.12 | 8.7±0.11 | 7.6±0.18a | 8.5±0.30a | 9.3±0.12ab | 7.6±0.14 | 8.5±0.10 | 7.8±0.22a | 8.4±0.57 | 10.3±0.55bc |
| Untreated control | 7.8±0.17 | 8.9±0.20 | 10.9±0.22b | 12.8±0.16c | 11.2±0.17c | 7.6±0.17 | 8.6±0.17 | 9.5±0.20c | 9.8±0.11 | 9.3±0.18b |
| **P value** | 0.85 | 0.073 | < 0.001 | < 0.001 | < 0.001 | 0.983 | 0.512 | 0.041 | 0.175 | 0.017 |
| **CV %** | 3.6 | 5.2 | 3.9 | 4.9 | 3.6 | 5.9 | 9.9 | 10.1 | 13.2 | 9.8 |

Figures presented are the means of each treatment. Means within a column are compared and separated using Tukey's test at $p<0.05$ and different letters indicate significant differences.

**Table 6: Mean percentage moisture content (±SEM) in cowpea stored on-farm using different treatments during a 32-week period during the 2018/19 storage season in Guruve and Mbire (n=4).**

| Treatment | Sampling period (weeks) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Guruve district | | | | | Mbire district | | | | |
| | 0 | 8 | 16 | 24 | 32 | 0 | 8 | 16 | 24 | 32 |
| Actellic Gold Dust® | 8.7±0.09 | 9.9±0.20ab | 10.9±0.08d | 11.1±0.59b | 9.2±0.23b | 8.9±0.06 | 10.6±0.15 | 10.4±0.13bc | 9.2±0.58 | 7.3±0.11 |
| ZeroFly® hermetic storage bag | 9.1±0.10 | 9.4±0.17a | 7.8±0.53a | 8.1±0.26a | 7.0±0.26a | 9.2±0.10 | 9.6±0.15 | 9.6±0.36abc | 8.9±0.37 | 10.7±0.90 |
| AgroZ® Plus bag | 8.7±0.25 | 9.2±0.05a | 9.7±0.26bcd | 8.7±0.21a | 7.1±0.21a | 9.1±0.06 | 10.0±0.31 | 8.2±0.23ab | 9.1±0.23 | 7.9±0.37 |
| AgroZ® Ordinary bag | 8.3±0.11 | 10.4±1.16ab | 8.0±0.34ab | 8.2±0.17a | 7.2±0.17a | 9.3±0.14 | 9.5±0.14 | 8.4±0.14abc | 9.3±0.57 | 8.2±0.70 |
| Purdue Improved Crop Storage (PICS) bag | 8.8±0.07 | 10.1±0.24ab | 9.0±0.12abc | 8.2±0.33a | 6.8±0.33a | 9.1±0.15 | 12.9±3.34 | 8.1±0.10a | 9.1±0.49 | 7.5±0.24 |
| GrainPro Super Grain bag (SGBs) IVR™ | 9.2±0.26 | 9.8±0.10ab | 9.8±0.74cd | 8.6±0.17a | 7.2±0.17a | 9.1±0.10 | 9.4±0.19 | 9.2±1.08abc | 9.4±0.40 | 7.8±0.65 |
| Untreated control | 8.6±0.16 | 11.8±0.34b | 11.3±0.39d | 10.9±0.29b | 9.2±0.29b | 8.9±0.12 | 10.3±0.05 | 10.6±0.31c | 9.6±0.16 | 7.4±0.09 |
| P value | 0.091 | 0.019 | < 0.001 | < 0.001 | < 0.001 | 0.419 | 0.525 | 0.005 | 0.842 | 0.104 |
| CV % | 3.8 | 9.5 | 7.8 | 6.1 | 4.0 | 2.5 | 22.3 | 10.4 | 9.5 | 13.2 |

Figures presented are the means of each treatment. Means within a column are compared and separated using Tukey's test at p<0.05 and different letters indicate significant differences.

### 3.6 Rodent and insect perforation of hermetic bag liners

During the 2017/18 storage season, rodents and *C. rhodesianus* larvae were responsible for most of the perforation of the hermetic bags. Rodent damage occurred on PICS bags and AgroZ® Plus bags in Guruve. Two rodent holes were observed on the same PICS bag. The rest of the damage was due to *C. rhodesianus* larvae and the holes were mainly on the bottom section (20 cm from the base seam) of the bags and on average were below five per bag (Fig. 6). In Mbire district, of the four households, rodent damage was recorded at only one of the households where an SGB and AgroZ® Plus bag had five and two big holes, respectively. Notably the number of *C. rhodesianus* holes on ZeroFly® hermetic storage bags at one of the households exceeded forty whereas all the other treatments had below five per bag.

In Guruve, no rodent damage was recorded on any of the treatments during the 2018/19 season. However, at two of the four households, AgroZ® Ordinary bag had a split base-seam. A few (< 5) larval emergence holes were recorded on the other hermetic bags, mainly the inner-most PICS liner. In Mbire district, rodents attacked one PICS bags and one AgroZ® Ordinary bag at separate households. One AgroZ® Plus bag had a split base-seam and one of the ZeroFly® hermetic storage bags recorded over 50 emergence holes while all other bags had on average below 5 emergence holes. No significant differences ($p<0.05$) were found between the number of holes recorded on the hermetic bags in both the 2017/18 and 2018/19 season in both districts.

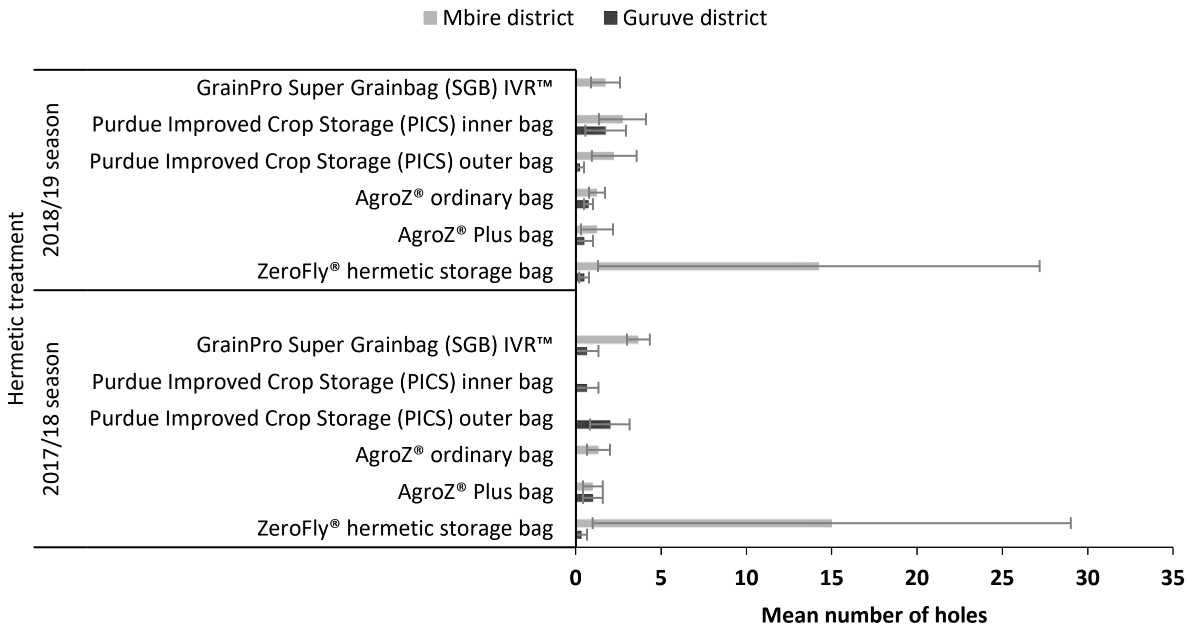



**Figure 6: Mean number of beetle boring holes on hermetic bags at the end of the 2017/18 and 2018/19 storage seasons.**

## 3.7 Overall site, season and treatment effect on grain damage, weight loss and moisture content

Grain damage was significantly higher in Mbire than Guruve. However, there were no significant differences with regards to moisture content and grain weight loss (Table 7). Grain damage and weight loss were significantly higher during the 2017/18 season than in the 2018/19 season (Table 8). Overall, hermetic treatments maintained approximately constant grain moisture content and had the least grain damage and weight loss compared to synthetic pesticide - Actellic Gold Dust® and untreated control (Table 9).

**Table 7: Overall site effect on grain damage, weight loss and moisture content.**

| Site | Grain damage (%) | Grain weight loss (%) | Moisture content (%) |
|---|---|---|---|
| Guruve | 12.08±1.08 | 2.74±0.23 | 8.96±0.08 |
| Mbire | 18.77±1.36 | 3.36±0.38 | 8.95±0.08 |
| P value | <0.001 | 0.161 | 0.938 |
| $F_{1,523}$ | 48.04 | 1.97 | 0.01 |

**Table 8: Overall season effect on grain damage, weight loss and moisture content.**

| Season | Grain damage (%) | Grain weight loss (%) | Moisture content (%) |
|---|---|---|---|
| 2017/18 | 23.96±1.29 | 5.01±0.37 | 8.78±0.07 |
| 2018/19 | 6.87±0.93 | 1.09±0.24 | 9.14±0.09 |
| P value | <0.001 | <0.001 | 0.001 |
| $F_{1,523}$ | 311.78 | 77.72 | 10.74 |

**Table 9: Overall treatment effect on grain damage, weight loss and moisture content.**

| Treatment | Grain damage (%) | Grain weight loss (%) | Moisture content (%) |
|---|---|---|---|
| Actellic Gold Dust® | 11.55±1.04a | 1.63±0.15a | 9.56±0.15b |
| ZeroFly® hermetic storage bag | 11.28±0.90a | 1.02±0.19a | 8.67±0.12a |
| AgroZ® Plus bag | 11.97±1.29a | 0.98±0.35a | 8.83±0.12a |
| AgroZ® Ordinary bag | 9.11±0.81a | 1.02±0.11a | 8.56±0.12a |
| Purdue Improved Crop Storage (PICS) bag | 8.88±0.89a | 0.82±0.21a | 8.62±0.21a |
| GrainPro Super Grain bag (SGBs) IVR™ | 8.45±4.21a | 0.89±1.20a | 8.72±0.17a |
| Untreated control | 46.68±1.02b | 15.02±0.24b | 9.73±0.12b |
| P value | <0.001 | <0.001 | <0.001 |
| $F_{6,523}$ | 48.04 | 80.75 | 11.24 |

Figures presented are the means of each treatment. Means within a column are compared and separated using Fishers test at p<0.05 and different letters indicate significant differences.

## 4.0 Discussion

All five of the different hermetic bag brands (AgroZ® Plus bag, AgroZ® Ordinary bag, ZeroFly® hermetic storage bag, PICS and SGB) evaluated were more effective in protecting stored cowpea from bruchid damage during a 32-week storage period than the untreated control, unless perforated by rodents and/or insects. A previous side-by-side comparison of PICS and SGBs in Niger also concluded that the two products were equally effective in suppressing insect damage in cowpea grains stored for five months in a laboratory storage room at ambient temperature (28-29°C) and relative humidity (5-30% rh) (Baoua et al., 2013). Effectiveness of hermetic containers was also reported by Aboagye et al. (2017) in storage of cowpeas grain under laboratory conditions for up 12 weeks in Ghana. However, it is important that grain storage trials are conducted over long time-frames of up to 8 months which give farmers flexibility in controlling the timing of their sales to maximize income returns. Effective long-term storage also enables the consumption of high quality grain through to the end of the storage season, and creates opportunities for use of the stored grain as seed in the next planting season as is common practice in SSA.

Incorporation of pesticides into either the outer woven bag (ZeroFly® hermetic storage bags) or the inner plastic liner (AgroZ® Plus bags) did not lead to lower damage of stored cowpea, nor did it result in reduced rodent damage of these bags. All hermetic bags containing cowpea grains had an equal chance of being perforated by rodents and insects. However, on-farm trials with maize grain in Malawi showed that the untreated control and Actellic Gold Dust® had higher incidences of rodent attack than hermetic bags where grain volatiles are sealed inside the bags (Singano et al., 2019). In the current study, three of the sixteen AgroZ® bags had a faulty base seam that split open during the storage period highlighting the need for higher quality control and manufacturing standards. Careful handling is required, especially when lifting and moving hermetic bags around.

Holding the outer polypropylene bag and not the liner is recommended to avoid damaging the liner. This problem was observed in Mbire where lifting of bags in and out of the storage granary was required during sampling, as there was not enough space for sampling them within the traditional granary.

The synthetic chemical pesticide, Actellic Gold Dust®, was as effective as the hermetic storage treatments in suppressing insect populations, insect grain damage and grain weight loss in on-farm stored cowpea grains. The active ingredients of synthetic pesticides differ, and so separate tests would need to be done to ascertain whether other synthetic pesticides would be equally as effective in reducing bruchid damage during cowpea storage.

The hermetic bags and Actellic Gold Dust® pesticide treatments kept grain weight loss and insect-generated dust below 5% in both districts and seasons. Bruchid pulse damage is not typically characterised by extensive dust production; instead numerous perforations on cowpea kernels and eggs-laid on their surface tend to occur, negatively impacting grain quality and seed viability.

Grain weight loss, damage and insect populations were high in the untreated control indicating the losses that farmers would incur if their cowpeas are left untreated for 32 weeks. However, in practice, due to this risk, farmers tend to dispose of the grain well-before it has sustained this damage level (Nyabako et al., in prep). Use of hermetic bags or Actellic Gold Dust® grain protectant, which cost US$1.50 and US$0.30 per 50 kg bag, respectively, allows farmers to avoid a storage loss of US$7.50 (50% weight loss) per 50 kg bag of cowpea grain which in Zimbabwe in 2019 had a value of US$15 just after harvest, rising to US$20 six months after harvest. In addition, hermetic bags may be used for two years, if not perforated, thus potentially increasing the economic benefits of using them.

Some hermetic storage facilities (ZeroFly® hermetic storage bags and AgroZ® bags) recorded higher insect infestation than other hermetic bags. This could have been due to perforations by rodents and open seams which allowed oxygen entry into the hermetic bags. *Callosobruchus maculatus* has previously been shown to cause small perforations on hermetic bags (Williams et al., 2016). Laboratory studies on the effects of leaks in hermetic bags conducted by Martin et al. (2015) concluded that seed damage increased markedly with each increase in number of holes on the bag liner. However, grain contributed a barrier to oxygen diffusion through the grain mass, hence the effect was localised. In the Martin et al. (2015) study, the perforations reported were small emergence holes caused by boring activities of adult bruchids when the hermetic bag is tightly packed, while in the current study, though these were also recorded, large perforations were observed and ascribed to rodent damage.

Perforations due to rodents enabled significant oxygen inflow into the bags resulting in insect proliferation and generalised grain damage. The insect and rodent damage in Mbire 2018/19 storage season on the ZeroFly® hermetic storage bags amplified the grain damage levels recorded. Whilst the repair method used by farmers of covering the perforations by tying bicycle tube rubber bands around the bags would reduce oxygen entry into the bags and help maintain hermeticity, farmers' maintenance response was, however, very poor and hence not effective in preserving the grain. Farmer monitoring of bags was irregular and some perforations were not noticed quickly or repaired promptly. In Niger, Baributsa et al. (2014) found that slightly damaged PICS bags with only a few holes were typically repaired with packaging tape and continued to be used effectively to store cowpea grain. Martin et al. (2015) reported that patching the holes in the hermetic bags with a single layer of HDPE film, was effective in reducing grain damage as observed under full hermetic conditions. However, access to such film or willingness to purchase it might prove challenging in some locations in developing countries. While patches could be made from an old HDPE bag or the top part of a HDPE bag, access to glue to make the patch stick may be difficult.

In Guruve, the number of perforation holes recorded in the hermetic bags were generally very low which can be attributed to the storage rooms used, which were large and easy to clean regularly as compared to the squashed compartmentalized traditional granaries used in Mbire. The crammed environment inside the traditional granaries was often conducive to rodent activity, which exposed the plastic bags to high risk of damage. The rodent damage recorded in this study, highlights the importance of integrated storage management and the need for good hygiene and rodent-proofing, alongside careful handling to optimize the outcomes of grain storage systems.

*Callosobruchus rhodesianus* is a destructive stored-product pest, as massive populations can build up in a short time which then exerts a lot of pressure on the stored grain causing high damage and losses in both quality and quantity (Silva et al., 2018), as occurred in the current study in both districts. The levels of insect counts and damage were higher in Mbire than Guruve, which could be attributed to higher ambient temperatures experienced in the former, which promotes more rapid proliferation of the insects.

The parasitic wasp, *D. basalis*, a natural enemy of cowpea weevils was mainly recorded in the untreated control when bruchid numbers were high. The wasp was only found at very low levels in the Actellic Gold Dust® and the hermetic treatments. These wasps are known to be highly susceptible to synthetic pesticides and low oxygen conditions, and typically only occur when bruchid numbers reach high levels (Kawuki et al., 2005). Despite it being abundant in the untreated control grain, this parasitoid was not sufficiently able to keep bruchid populations low, suggesting that some other measure of protection is required. In other studies, the larval parasitoids, *Anisopteromalus calandrae* and *Lariophagus distinguendus* (Hymenoptera: Pteromalidae) were found to be effective in reducing *Callosobruchus chinensis* (L.) (Coleoptera: Chrysomelidae) larval population in stored chick peas under laboratory controlled conditions (28 ± 2 °C, 75 ± 5% RH) (Iturralde-García et al., 2020).

During the 2018/19 storage season, damage was very low (<5%) in all the treatments in Guruve district including the untreated control. This could have been due to a low rate of cross-infestation in Guruve as the farmers generally produce and store small quantities of cowpeas for short periods unlike in Mbire where cowpea production and storage occurs on a much larger and longer scale. Farmers in Guruve store grain in their houses under more hygienic conditions than in the granaries used in Mbire, which helps reduce the chances of cross-infestation from neighbours. In addition, the cowpea grains were stored soon after harvest when infestation levels were still very low, unlike in the 2017/18 where infestation levels were higher at trial set up.

Grain moisture content was maintained in hermetic treatments (≤ 9%), but once the hermetic bags were perforated, inconsistent trends in moisture content were observed. The grains stored in just a woven polypropylene bag have a much greater interaction with the environment than those stored in hermetic gas-tight bags and this interaction with the environment typically leads to the moisture content fluctuating in response to changes in ambient relative humidity (Mlambo et al., 2017). The low grain moisture content of less than 8% at trial set-up in our experiments, has in other studies been reported to promote *C. maculatus* mortality under hermetic storage (Baoua et al., 2012). High temperatures, as recorded during the season in Mbire, also increase insect metabolism and the demand for oxygen leading to more rapid hypoxia in hermetic conditions (Martin et al., 2015). Low relative humidity as experienced in Mbire, accelerates loss of insect body water, which hastens insect death by desiccation (Baoua et al., 2012).

The use of a multi-compartmental sampling spear for sampling the bags was a limitation in the study as the total insect counts in samples within one treatment fluctuated between samplings. Dead adult insects typically fall to the bottom of the bag, and would thus be missed during sampling, leading to fluctuations in the insect numbers recorded.

Although hermetic bags demonstrated effectiveness, only GrainPro Super Grain bag (SGBs) IVR™ is currently available on the Zimbabwean market. None of the bags, are manufactured locally in Zimbabwe yet, which can push prices up which then negatively affects adoption. GrainPro Super Grain bags (SGBs) IVR™ cost US$1.50 per bag in the Zimbabwean retail market as compared to US$1.00 USD in the Philippines where they are manufactured.

The study focused on quantitative losses of cowpeas during storage. Thus further study on the effect on nutritional composition and germination potential during storage in hermetic bags is recommended. In other studies, hermetic storage has been found to retain grain viability as germination is negatively correlated to damage, weight loss, and insect population in the grain samples (Sanon et al., 2011; Murdock et al., 2012; Chigoverah and Mvumi, 2018). This is important for cowpeas farmers in SSA who often retain and recycle the grain as seed (Dhliwayo and Pixley, 2003).

In conclusion, all the hermetic bag brands and the synthetic pesticide, Actellic Gold Dust® were shown to be more effective in protecting stored cowpea grain from insect attack under smallholder farming conditions than the untreated control. Insect pest numbers, grain damage, and weight loss remained low in the hermetic bags tested, resulting in a higher proportion of wholesome and edible grain during 32 weeks of storage. The hermetic bags maintained the grain moisture content better than the non-hermetic methods studied. Based on these findings, we recommend promotion of hermetic bags as part of an integrated postharvest management approach for smallholder farmers to use. Hermetic bags can replace the use of chemical storage pesticides in cowpea storage, reducing the associated health-risks. In our trials, all the hermetic bag brands studied were equally affected by rodent attack, highlighting the importance of good hygiene, rodent-proofing and control in storage facilities to reduce the likelihood of the hermetic bags being perforated and rendered ineffective. In addition, multiple handling of hermetic bags is discouraged as it may lead to bags splitting along their base seams and thus reducing their efficacy.

Use of hermetic bags can help reduce quantitative and qualitative PHLs, thereby enabling smallholder farmers to earn higher incomes through sale of high quality cowpea and through sales at times during the season when the market prices are higher, rather than selling immediately after harvest to avoid losses. Reduction in PHLs will also ensure household food and nutrition security, helping to mitigate malnutrition.

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