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On-farm comparison of different postharvest storage technologies in a maize farming system of Tanzania Central Corridor

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ABSTRACT

Seven methods for storing maize were tested and compared with traditional storage of maize in polypropylene bags. Twenty farmers managed the experiment under their prevailing conditions for 30 weeks. Stored grain was assessed for damage every six weeks. The dominant storage insect pests identified were the Maize weevil (*Sitophilus zeamais*) and the Red flour beetle (*Tribolium castaneum*). The moisture content of grain in hermetic conditions increased from $12.5 \pm 0.2\%$ at the start of storage to a range of 13.0 ± 0.2–$13.5 \pm 0.2\%$ at 30 weeks. There was no significant difference ($F = 87.09$; $P < 0.0001$) regarding insect control and grain damage between hermetic storage and fumigation with insecticides. However, the insecticide treatment of polypropylene yarn (ZeroFly®) did not control the insect populations for the experimental period under farmers' management. Grain damage was significantly lower in hermetic storage and fumigated grain than ZeroFly® and polypropylene bags without fumigation. No significant difference in grain damage was found between airtight treatment alone and when combined with the use of insecticides. During storage, *S. zeamais* was predominant and could be of more economic importance than *T. castaneum* as far as maize damage is concerned. At 30 weeks, the germination rate of grain stored with insecticides or in hermetic storage ($68.5 \pm 3.6\%$ to $81.4 \pm 4.0\%$) had not significantly reduced from the rate before storage ($F = 15.55$; $P < 0.0001$) except in ZeroFly®, also in polypropylene bags without treatment. Even though such bags did not control storage pests, farmers still liked this cheap technology. Hermetic storage techniques can be recommended to farmers without the use of insecticides provided they are inexpensive, and the proper application of technologies is ensured.

1. Introduction

Postharvest loss, the quantitative and qualitative loss of food value in food crops until they reach the consumer, is a leading cause of food insecurity in sub-Saharan Africa (SSA) (Chigoverah and Mvumi, 2016). In Eastern and Southern Africa alone, postharvest loss (PHL) of grain can be valued at US$1.6 billion/year, or about 13.56% of the total value of grain production in the region, and could potentially reach nearly US$4 billion/year in SSA out of an estimated annual value of US$27 billion (Zorya et al., 2011). Maize is grown on an average of 2 million ha or about 45% of the cultivated land in Tanzania and is a staple food for the majority of the population (FSD, 1996; Kimanya et al., 2008). It provides about 60% of their dietary energy intake and about 50% of their digestible protein intake (Katinila et al., 1998).

Maize is one of the crops most severely affected by PHL (FAO, 1998; Abass et al., 2014). On-farm PHL of maize outweighs that encountered in other food chains in SSA (Heinrichs and Muniappan, 2016). According to Oerke et al. (1994), an average of 35% of crop yields is lost to pre-harvest pests and 10–20% to postharvest pests worldwide, but field loss due to pests varies considerably. According to APHLIS, postharvest weight loss for maize in Tanzania

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(from harvest to market storage) fluctuated between 16 and 23% across different regions. Based on a survey, Abass et al. (2014) reported farmers' estimates of 25–40% of total crop loss from the field until final marketing. Major losses of stored grain are caused by insect pests especially the larger grain borer (LGB), *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae), the Red flour beetle (*Tribolium castaneum*), and the Maize weevil (*Sitophilus zeamais* Motschulsky) (Coleoptera: Curculionidae) (Golob and Hanks, 1990). Particularly in small-scale and on-farm storage, *P. truncatus* is more damaging than *S. zeamais* although its occurrence is seasonal. Previous studies have indicated that the major environmental factors determining the survival of insect pests in grain storage facilities are related to the interstitial air quantity (or oxygen and CO_2 concentrations), air temperature and relative humidity, grain composition, grain moisture content before storage, and nutrient content, as well as the conditions of the storage environment (Zhou et al., 2000; Frazier et al., 2001; Ofuya and Reichmuth, 2002; Assie et al., 2008; Williams et al., 2014, 2017; Đukic et al., 2016).

If the grain is dried to an appropriate moisture level of 12–13% storage insects can be controlled effectively with fumigants such as Phostoxin (Hodges, 1986). In Tanzania, farmers are allowed to use Phostoxin if supervised by authorized extension agents, but the effectiveness of such arrangements at the community level is yet to be ascertained. Farmers widely use a mixture of Pirimiphos-methyl (Actellic) and Permethrin, commercially sold as Actellic Super (local name: *Shumba*) but farmers are often unable to verify the genuineness of some local brands.

More recently there has been an increasing number of studies on the use of hermetically sealed containers to control storage insect pests, based on the oxygen depletion mechanism that rapidly occurs in the containers causing an increase in CO_2 concentration and death of the pests (Yakubu et al., 2011; Murdock et al., 2012; Baoua et al., 2013; De Groote et al., 2013; Moussa et al., 2014; Chigoverah and Mvumi, 2016; Likhayo et al., 2016; Midega et al., 2016). Metal silos have been heavily promoted in Central America (Bokusheva et al., 2012) but with the use of fumigation with Phostoxin. They are now also being promoted in SSA, but the level of adoption by smallholder farmers is still low due to their relatively high initial investment cost and limited availability (Baoua et al., 2014). Flexible hermetic storage systems, such as Purdue Improved Crop Storage (PICS) bags, super grain bags (SGB), cocoons, and others, are being tested to control storage insect pests in Asia and different African countries (Quezada et al., 2006; Phiri and Otieno, 2008; Baoua et al., 2013, 2014; Jones et al., 2014). To reduce costs, recycled hermetic containers are now being sought by farmers to provide low capacity and efficient storage of grain (Yakubu et al., 2011). SGB suffered substantial damage from *P. truncatus* during long-term maize storage trials in Kenya and Bénin (De Groote et al., 2013). However, Chigoverah and Mvumi (2016) observed that some of the studies were conducted in a laboratory environment using laboratory methods of assessment; the studies were managed by researchers and carried out for a short time or did not last throughout the typical storage seasons practiced by farmers in many African countries. Hence the potential adaptability of the technologies and their acceptance by farmers as alternatives to the use of insecticides could be in question. There is a need for additional scientific and sociocultural evidence on the relative effectiveness and acceptability of different hermetic storage materials under actual on-farm conditions and farmers' management practices across different agro-ecologies and with insects of diverse types. Hence, this study was conducted in the Central Corridor of Tanzania (covering semi-arid/Sudan Savanna (SS), Northern Guinea Savanna (NGS), and Southern Guinea Savanna (SGS) agro-ecologies) to ascertain the effectiveness of different storage technologies for maize and establish the feasibility of small farmers applying the principle of hermetic storage without losing the desired grain quality.

2. Materials and methods

2.1. Description of the experimental sites

The experiment was carried out from October 2014 to May 2015 in two regions (Dodoma and Manyara) in the Central Corridor of Tanzania. In each region, two villages were selected based on maize production, agroclimatic conditions, good access to roads, the importance of maize in the farming system, and total village population of at least 250 residents. In each village, five households were randomly selected, based on willingness to participate in the experiment, availability of space in the home to keep all the storage treatments, and ability to manage the experiment. Thus, 20 farmers were involved in the experiment in all four villages located in three agro-ecologies: two in Dodoma region Kindagali: −05.9333333°, 035.5833333° within the SS and Kibaigwa: −6.078545, 36.645509 within the NGS, and two in Manyara region Endagaw: −4.4065716, 35.5494538 and Endasaki: −4.419066, 35.511143, both within the SGS.

2.2. Experimental details

Shelled maize with natural infestation harvested between July and September 2014 was used from each village for the experiment. Each household had eight storage treatments as follows. (i) *Metal silo hermetic*: Hermetic storage of untreated maize using a metal silo filled to 90% of the 500 kg capacity. (ii) *Metal silo phostoxin*: Hermetic storage using a metal silo filled to 90% of the 500 kg capacity with a Phostoxin-treated grain (active ingredient is aluminum phosphide, 57% w/w). (iii) *Plastic barrel hermetic*: Hermetic storage of untreated grain using a plastic barrel (a flat-topped 150-L high-density polyethylene container) filled to 90% of its capacity. (iv) *Plastic barrel Photoxin*: Hermetic storage of Phostoxin-treated grain using a plastic barrel filled to 90% of its capacity. (v) *PICS*: Hermetic storage of 100 kg of untreated grain using two 100-kg Purdue Improved Crop Storage (PICS bags, described by De Groote et al., 2013) purchased from Pee-Pee Tanzania Ltd, Tanga, Tanzania. (vi) *ZeroFly*®: Storage of 50 kg of untreated grain using a ZeroFly® storage bag (non-hermetic; polypropylene bag with deltamethrin insecticide incorporated at the rate of 3 g/kg ± 25%) purchased from Vestergaard, Lagos, Nigeria, and shipped by airfreight to Tanzania. Four 50-kg bags were used. (vii) *PP Shumba*: Storage of 100 kg of grain treated with Actellic Super® (Pirimiphos-methyl 16 g/kg plus Permethrin 3 g/kg) in polypropylene (PP) bags (non-hermetic). This is the common farmers' practice known as *Shumba* in Tanzania. Two 100-kg bags were used. (viii) *PP without treatment*: Storage of untreated grain in polypropylene (PP) bags (non-hermetic) commonly used to transport and store grain. Two 100-kg bags were used (control).

Maize was treated using aluminum phosphide tablets (Phostoxin treatment) according to the manufacturer's guide by a trained member of the staff of the District Agricultural Extension Service. Each bag was properly secured at the mouth to prevent maize spillage and maintain hermetic sealing in PICS. Similarly, the inlet (the main opening on the top) and the bottom outlet of all silos and the only outlet on the top of the plastic barrels were covered with a lid and sealed with a rubber band. Soap was used to further seal the inlets and outlets of the plastic barrels and silos to maintain hermetic sealing, following the method of Tefera et al. (2011). However, since it was unlikely that smallholder farmers would be applying oxygen depletion inside the silos and barrels, oxygen was not depleted with the candle method as described by Tefera et al.

(2011). One metal silo, one plastic barrel, and different bags at each household were not opened until the containers were sampled at the end of the 30 weeks of the study.

2.3. Measurements of environmental and storage conditions during the experiment

The environmental humidity (H_{out}) and temperature (T_{out}) were monitored (6-hourly) using electronic data loggers *(Dickson TK550 model)* in the experimental rooms of the selected households. The relative humidity (H_{in}) and temperature (T_{in}) inside the storage facilities were recorded using data loggers placed inside four representative treatments (*Hermetic metal silo, Hermetic plastic barrel, PICS bag, and PP bag without treatment*) and in only two out of five households/village with the assumption that (i) the temperature and humidity conditions inside *PP without treatment* would be the same as the conditions in *PP Shumba* and *ZeroFly*®, (ii) the conditions inside the *Hermetic metal silo* would be the same as the conditions inside *Metal silo with Phostoxin,* and (iii) the conditions inside the *Hermetic plastic barrel* would be the same as the conditions inside the *Plastic barrel with Phostoxin.* Data were downloaded from the data loggers at each sampling date.

2.4. Grain sampling and field assessments

Sampling: Maize samples were obtained from storage containers using different types and sizes of compartmentalized sampling probes or spears (Seedburo Equipment Co., USA). A 1.8 m aluminum probe of 12 openings was used to take samples from metal silos and plastic barrels; a brass open-handled probe of six openings was used to take samples from ZeroFly®, PICS, and PP bags. Samples were taken from the center and four peripheral and equidistant points perpendicular to the center of each storage container, thereby making a total of five samples from each container. A representative sample (1 kg) from each treatment was transferred into a labeled paper bag, sealed, and then transported to the laboratory for further analysis. All samples were stored at ambient conditions until processed.

Grain moisture (GM) and Bulk Density (BD): A representative sample was tested for percentage grain moisture (GM), and bulk density (BD) or volumetric weight (g/cm^3) using a hand-held grain moisture tester (Dickey-John GAC ® Plus, Illinois, USA) calibrated according to the US Federal standard grain calibration.

2.5. Laboratory assessment

Insect counts: The type and population of insects were visually evaluated in the laboratory following the method described by Ng'ang'a et al. (2016).

Grain assessment: In the laboratory, samples were visually examined for broken and damaged grain (DG) using the 1000 grains count. The percentage DG was calculated following the formula described by Boxall (1986). Weight loss (WL) was calculated as shown by Njoroge et al. (2014).

According to the cause(s), DG was further separated into different categories; (i) Insect damage: insects only, insects and fungi only, (ii) Fungal damage: fungi only, germination and fungi only, rodents and fungi only, other damage and fungi only, (iii) Grain breakage: broken grain only, (iv) Stunting: stunted grain.

Germination test: Selected maize samples were tested for percentage germination three times during the storage period: (i) at base condition (before storage) when a representative sample of maize from the bulk to be stored was collected from each of the 20 households (20 samples), (ii) 175 samples were collected at 18 weeks of storage, and (iii) 175 samples were collected at 30 weeks of storage. Sand sub-strata were prepared and used as growing media. A random sampling of 400 grains from each lot was followed with sub-sampling of 100 grains for sowing. The grain was sown in trays placed at a depth of 5 cm in the moistened sand before sowing and irrigated on a daily basis with potable water. The counting of germinated grains was conducted on day five and day eight after sowing. Three counts were made each time.

In all cases, the moisture content and BD using a GAC meter, the types and populations of insects, holes caused by insects, discoloration by mold, shriveling and other signs of deterioration, WL, and germination percentage were examined and recorded as the base condition.

2.6. Farmers' perceptions of the storage technologies

The participating farmers (20 respondents: 6 female, 14 male; 70% aged between 40 and 60 years) were asked to rate the storage technologies according to their perceptions about effectiveness to prevent grain loss and how the farmers liked the storage technologies.

2.7. Data analysis

Data were entered into an Excel spreadsheet and analyzed using SAS® version9.4 (SAS Institute, Cary, NC) to determine means and frequencies to explain the data pattern. Percentage values were transformed to new values (Y) using Arcsine transformation parameter (X) as follows:

$$Y = \left(Arc\,\sin\sqrt{(\text{Parameter}(X)/100)}\right) \times 180/3.14 \tag{1}$$

The transformed variable was then used for analysis of coefficient of interaction.

The ANOVA procedure MEANS statement was used for analysis of variance (ANOVA) to identify significant differences between sample means. Where significant differences were revealed, a stepwise multiple comparisons GLM procedure was used for the Tukey-Kramer multiple comparisons test to determine the pattern of differences in the samples. Significant differences in storage parameters were concluded when the coefficient of the interaction term was significant at $P < 0.05$, $P < 0.01$, or $P < 0.001$ as the statistical significance levels. Additionally, standard errors were calculated and used as means separation tests.

3. Results and discussion

3.1. Relative humidity and temperature conditions during the experiment

Table 1 shows the relative humidity (H_{out}) and temperature (T_{out}) that were measured with data loggers depicting the average environmental weather conditions of the experimental sites in the two regions. Similarly, T_{in} (°C) and H_{in} (%) are the average temperature and relative humidity, respectively, that were measured with data loggers depicting the prevailing conditions inside four selected representative treatments as follows. (i) PP without treatment representing the conditions of maize inside PP bags without insecticide treatment, ZeroFly®, and PP *Shumba.* (ii) PICS. (iii) Metal silo hermetic representing the conditions of maize inside all metal silos with or without insecticide treatment. (iv) Plastic barrel hermetic is representing the conditions of maize inside all plastic barrels with or without insecticide treatment during the entire period of storage.

Manyara experimental sites had higher mean relative humidity (70.5 ± 0.61%) than Dodoma sites (66.5 ± 1.16%) during the storage period. Also, the average temperature (T_{out}; °C) in Manyara sites

Table 1
Average (±SE) prevailing relative humidity and temperature of the experimental sites and inside representative storage containers.

Storage condition	Storage technology	Dodoma sites	Manyara sites	*P*-values
Atmos. Humidity (H_{out}; %)		66.50 ± 1.16	70.50 ± 0.61	<0.05
Storage Humidity (H_{in}; %)	Metal Silo Hermetic	61.68 ± 0.94	75.32 ± 0.25	<0.0001
	Plastic barrel hermetic	60.15 ± 0.70	73.28 ± 1.11	<0.0001
	PICS	60.02 ± 0.74	72.47 ± 0.87	<0.0001
	PP without treatment	58.52 ± 0.85	62.28 ± 1.70	0 .68
Atmos. Temp (T_{out}; °C)		26.00 ± 0.84	23.50 ± 0.14	<0.05
Storage Temp (T_{in}; °C)	Metal Silo Hermetic	26.39 ± 0.26	24.75 ± 0.38	0.001
	Plastic barrel hermetic	25.82 ± 0.16	24.31 ± 0.29	<0.0001
	PICS	26.00 ± 0.17	24.03 ± 0.30	<0.0001
	PP without treatment	28.68 ± 0.60	30.62 ± 0.85	0.06

was 23.50 ± 0.14 °C, while Dodoma sites had a higher average temperature of 26.0 ± 0.84 °C. For most of the storage period, Dodoma experimental sites (SS and NGS) were drier and hotter than the SGS experimental sites in Manyara.

Nevertheless, the mean relative humidity maintained inside hermetic storage containers was significantly higher (72.47 ± 0.87% to 75.32 ± 0.25%) in Manyara sites than in Dodoma sites (60.02 ± 0.74% to 61.68 ± 0.94%) but the average humidity conditions in PP bags without treatment in Manyara (62.28 ± 1.70%) is similar to the average humidity in Dodoma (58.52 ± 0.86)%. However, the temperature maintained inside hermetic storage containers (metal silos, plastic barrels, and PICS) were higher in Dodoma sites (25.82 ± 0.16 °C to 26.39 ± 0.26 °C) than in Dodoma sites (24.03 ± 0.30 °C to 24.75 ± 0.38 °C) but no difference I temperature between the two sites for PP bags without treatment (28.68 ± 0.60 °C in Dodoma and 30.62 ± 0.85 °C in Manyara sites). According to Chiappini et al. (2009) and Baoua et al. (2012), the Sahelian agroecology with relatively higher temperatures (e.g., 28–39 °C) and low humidity (e.g. < 20%) may increase the oxygen demand and desiccation of insect pests such as *T. castaneum* leading to high mortality, the environmental conditions found at the at all the experimental sites of both Dodoma and Manyara seem to be less harsh for the spoilage insects.

On the other hand, the higher average humidity in Manyara sites, both atmospheric and inside the airtight containers, may indicate potentially higher risks of mold spoilage than in the Dodoma sites. At both sites, the average prevailing relative humidity in airtight containers are higher than inside non-hermetic containers (PP bags without insecticide treatment, ZeroFly®, and PP *Shumba*). The implication is that farmers in more humid environments need to be well aware of the need to store well-dried grain whenever hermetic containers are to be used for extended storage periods.

The temperature inside PP bags without treatment, representing non-hermetic containers (PP bags without insecticide treatment, ZeroFly®, and PP *Shumba*), increased above the environmental temperature and more than the temperatures inside hermetic storage conditions (PICS, plastic barrels, and silos). The higher average temperatures suggest that the heat was most likely generated by high insect populations inside the non-hermetic bags (perhaps excluding inside PP *Shumba* where high insect population is unexpected). In a study done in Kenya, Ng'ang'a et al. (2016) observed similar significantly more elevated temperatures of maize stored in PP bags (28.2 ± 0.5 °C) and jute bags (28.6 ± 0.6 °C) than in PICS bags (25.7 ± 0.4 °C).

3.2. *Grain moisture (GM)*

Maize stored in hermetic storage containers had a higher GM content than in non-hermetic bags (ZeroFly®, PP *Shumba,* and PP bags without treatment; Fig. 1). The moisture content of grain stored in non-hermetic conditions (ZeroFly®, PP bags) reduced until week 18 of storage and increased slightly afterward. The moisture content of grain in hermetic conditions (silos, plastic barrels, PICS) was in the range of 12.95 ± 0.06–13.54 ± 0.2% at 30 weeks of storage, increasing from 12.48 ± 0.18% at the time of storage. These values were significantly higher than the moisture content of the maize stored in the non-hermetic facilities (especially the PP bags) that had a moisture content of 12.36 ± 0.08% at 30 weeks of storage. In fact, during the field experiment, we observed high moisture condensation under the lids of some metal silos, plastic barrels, and the upper inner-layer of PICS bags. Increase in GM during storage could negatively affect grain quality and seed viability (Tubbs et al., 2016). Cellular respiration of grain and insects within the container to use some of the stored glucose and available oxygen metabolically would lead to the production of CO_2, water, and energy (Adenosine triphosphate, or ATP) (Murdock et al., 2012). Soon after depletion of O_2 through respiration, the production of water and activities of insects would stop. However, intermittent opening of the containers could lead to the accumulation of moisture.

These results of 30 weeks of storage (the typical period for storage of maize by farmers before the next harvest season) are in contrast with the results of a shorter duration (8-week) study of maize seeds in Afghanistan that found the moisture content of the seeds (10 kg/trial batch) increased in PP bags while it remained constant in PICS (Afzal et al., 2017). The result is, however, consistent with the findings of Williams et al. (2014) and Ng'ang'a et al. (2016); these showed that the moisture content of maize stored in PICS bags increased during long storage periods while the moisture content of grain reduced in PP bags and jute bags.

3.3. *Bulk density (BD) of stored grain*

Bulk density (BD) measures the weight of grain to fill a specific volume. It is used as a commercial classification during trading of maize (Santos et al., 2010). Typically, maize with moisture content between 12 and 16% is tested for BD during trading. It is also an index for the selection of new varieties for processing into food items, e.g., as a proxy for endosperm hardness when new maize varieties are evaluated. The BD of stored grain decreased from the starting value of 774.8 ± 4.3 kg/m^3 (at the start of storage) to between 741.9 ± 4.3 kg/m^3 and 766.7 ± 4.6 kg/m^3 at storage Week 6 in all the storage conditions (Fig. 2). The BD of the grain in ZeroFly® and PP bags decreased to 699.0 ± 6.2 kg/m^3 and 673.5 ± 7.4 kg/m^3, respectively, at the end of storage. This reduction in BD appears to be influenced by insect damage to the kernel (food loss). On the other hand, the BD for treated grain in polypropylene (PP *Shumba*) and untreated maize in airtight containers (≥752.3 ± 2.9 kg/m^3) suggest less dry matter loss.

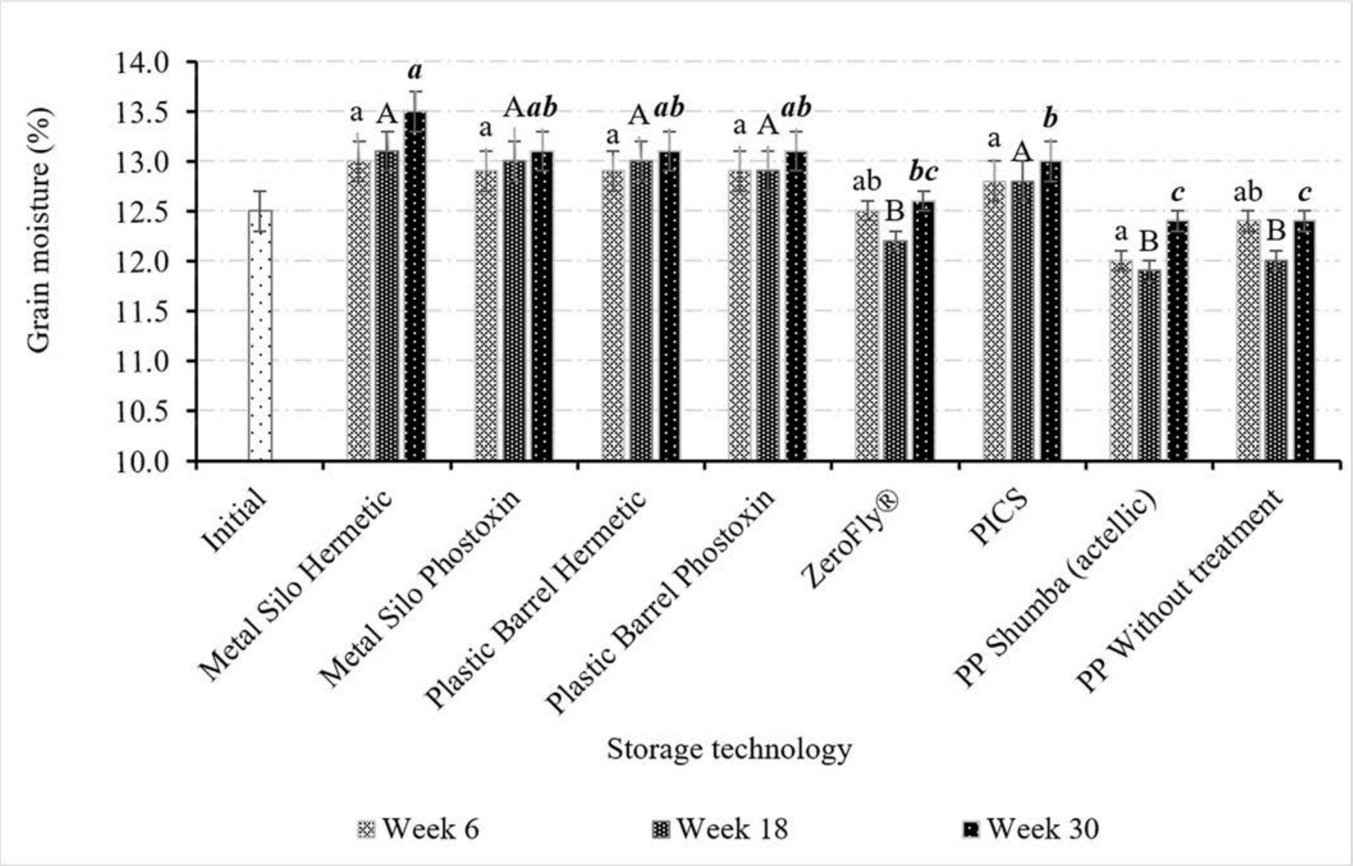

Fig. 1. Percent (Mean ± SE) grain moisture in the storage technologies over 30 weeks of storage.
Foot note: Significant difference between means for % Grain moisture at Week 6 denoted by different lower case letters (F = 5.04, P < 0.0001), significant difference between % Grain moisture at Week 18 denoted by different upper case letters (F = 11.46, P < 0.0001), significant difference between % Grain moisture at Week 30 denoted by different bold lower case letters in ***italics*** (F = 7.69, P < 0.0001).

3.4. Insect population

Two major maize spoilage insects were identified: *S. zeamais* and *T. castaneum*. We did not find *P. truncatus* throughout the storage period.

The population of live adult *S. zeamais* in the grain increased rapidly from 34 ± 7.7 per 1000 grains at the beginning of storage to 318 ± 89.6 per 1000 grains in ZeroFly$^{®}$ and 138 ± 25.3 in PP bags at 30 weeks (Fig. 3). On the other hand, the population reduced to between 3 ± 1.4 and 27 ± 10.6 per 1000 grains in all the airtight containers (PICS, metal silo Photosxin, plastic barrel Photoxin) with treated or untreated grain. The insect was completely absent in PP *Shumba* (Actellic).

The observed increase in insect population in metal silos and plastic barrels at week 30 after an initial decrease in population (Week 6) may be as a result of imperfect sealing or closure in a few of these containers, which may be suggestive of one of the risks of the use by farmers of metal silos and plastic barrels.

At the end of storage the number of dead *S. zeamais* adults per 1000 grains was highest in ZeroFly$^{®}$, rising from 5 ± 1.6 at the storage time to 238 ± 32.7, and in PP bags, to 57 ± 14.3 (Fig. 4). For the other treatments, the number of dead *S. zeamais* adults was much lower at week 30. It was between 8 and 27 for all hermetic treatments. PICS had the lowest number, 9 ± 3.1, of dead *S. zeamais* adults, significantly fewer than in other treatments (F = 28.01; $P < 0.0001$).

Adult *T. castaneum* was not detected at the time of storage but later detected during storage (Figs. 5 and 6). At week 30 of storage, the population of live *T. castaneum* adults was low (1 ± 0.8 to 13 ± 6.2 insects per 1000 grains) in all airtight containers and insecticide-treated grain (1 ± 0.74 insects per 1000 grains) while it was significantly higher in ZeroFly$^{®}$ and PP bags (without treatment), with values of 64 ± 22.0 and 66 ± 9.7, respectively, at week 30 of storage (F = 33.98; $P < 0.0001$). Among the airtight containers, the metal silo with untreated grain had the highest population of *S. zeamais* (13 ± 6.2).

An average of 7 ± 1.6–11 ± 3.8 dead adult of *T. castaneum* per 1000 grains was found in ZeroFly$^{®}$ and PP bags, none or at most one dead adult of *T. castaneum* was found in hermetic storage containers and also in grain treated with insecticides.

It appears that under farmers' management ZeroFly$^{®}$ was not effective in preventing an increase in the population of *S. zeamais* or *T. castaneum* and only 14.7–42.8% of the insect population was dead at week 30 of storage. On the other hand, hermetic storage or insecticides could more easily control *T. castaneum* population.

The results corroborated other findings that hermetic conditions are effective against insect proliferation (Baoua et al., 2012, 2014) and that *S. zeamais* was more numerous than *T. castaneum* and responsible for the more substantial proportion of maize damage (Afzal et al., 2017). However, this study seemed to show that the effectiveness of the metal silo under the farmers' conditions could be affected, taking into account the farmers' practice of repeatedly opening their storage containers to withdraw household food; this is also consistent with the results obtained by N'gan'ga et al. (2016).

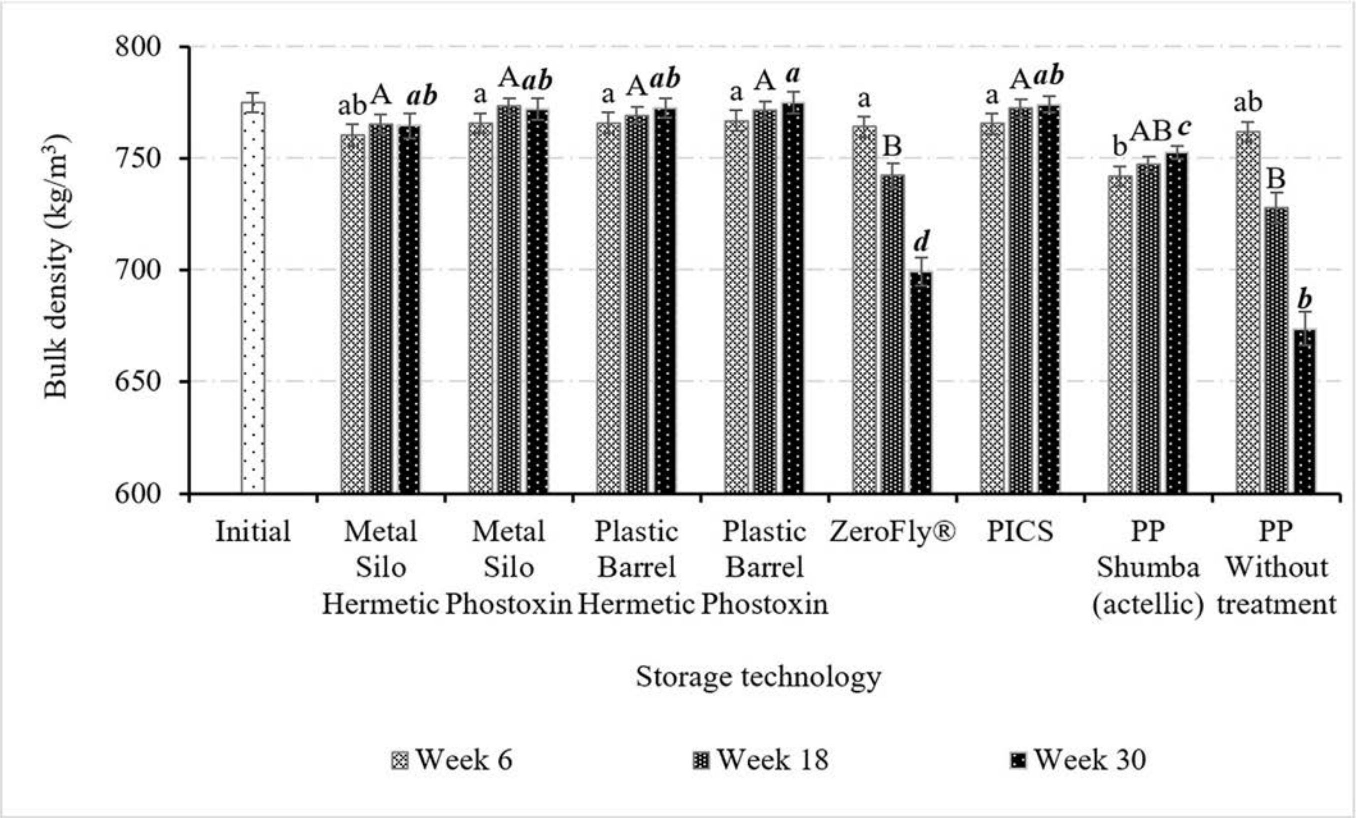

Fig. 2. Grain bulk density (mean ± SE) in the storage technologies over 30 weeks.
Significant difference between means of bulk density (k/m^3) at Week 6 denoted by different lower case letters (F = 3.16, P = 0.0038), significant difference between means of bulk density (k/m^3) at Week 18 denoted by different upper case letters (F = 11.23, P < 0.0001), significant difference between means of bulk density (k/m^3) at Week 30 denoted by different bold lower case letters in ***italics*** (F = 49.85, P < 0.0001).

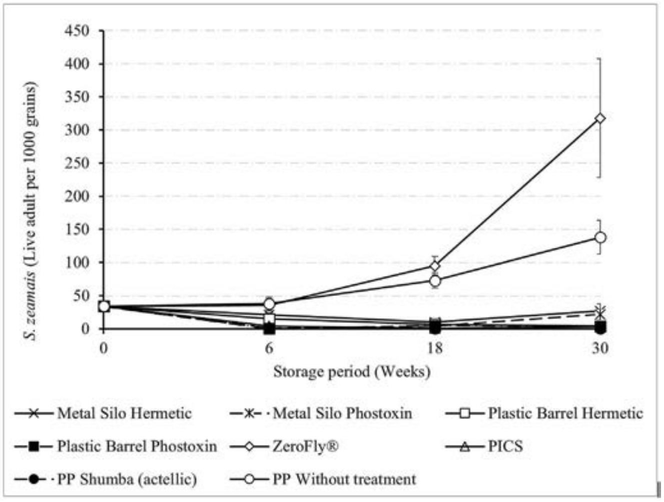

Fig. 3. Number (mean ± SE) of live *S. zeamais* adult population in the storage technologies over 30 weeks.

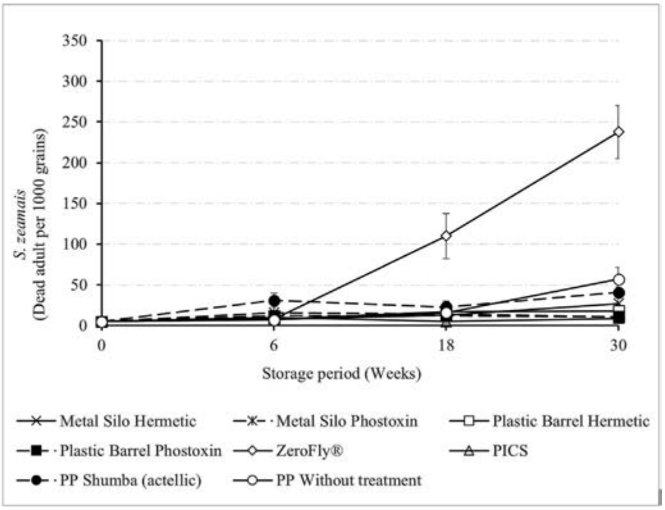

Fig. 4. Number (mean ± SE) of dead *S. zeamais* adult population in the storage technologies over 30 weeks.

3.5. Grain damage (DG)

Fig. 7 reveals very crucial patterns of insect behavior concerning the destruction of grain and the consequent food loss during storage if farmers would adopt the various storage technologies tested. The results reveal the implication of poor shelling methods that break the grain before storage and how this could accentuate insect damage.

According to the technique of Boxall (1986) used for the study, DG is the comparative weight of damaged grain to a batch of wholesome or undamaged grain. DG was 11.49 ± 0.8% at the beginning of the storage experiment. During storage, there was an initial decrease in DG at week 18 after which DG values increased.

The increases were highest in PP bags (PP without treatment)

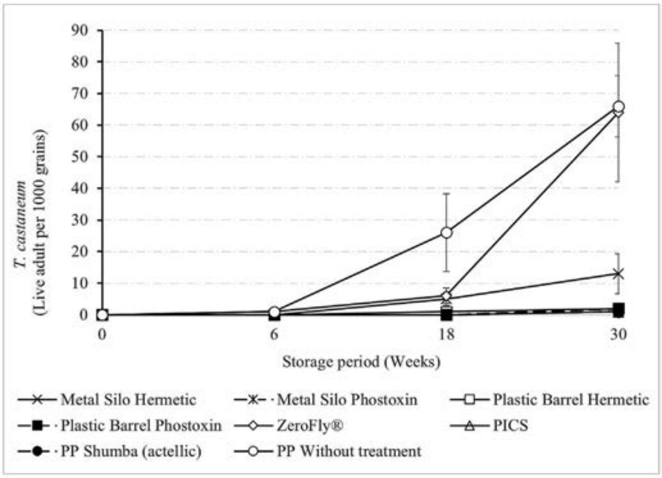

Fig. 5. Number (mean ± SE) of live *Tribolium castaneum* adult population in the storage technologies over 30 weeks.

reaching 58.3 ± 2.5% and in ZeroFly® bags, reaching 42.2 ± 3.1% at week 30 of storage, and were significantly higher (F = 87.09; $P < 0.0001$) than the DG percentage in all the other storage treatments that were in the range of 7.0 ± 0.7% to 10.9 ± 1.5%. However, no significant differences were observed among the remaining treatments irrespective of the use of insecticide whether combined with hermetic storage or not. Hence, the airtight storage containers were effective in preventing grain damage without the use of insecticides. The result agrees with those obtained by Baoua et al. (2013) that the use of Phostoxin insecticide in combination with PICS did not improve the preservation of maize grain to any significant extent. Paudyal et al. (2017a & b) found the treatment of polypropylene yarn with insecticides to be effective in both a contact sensitivity test and during actual field storage for 16 weeks but the kernel damage was more than 10% from 6 months of storage. The current study also showed that the insecticide-treated PP bags (ZeroFly®) did not significantly control the insect population under smallholders' management and storage of field-infested grain over an extended storage period. Đukic et al. (2016) observed that the initial population density and type of diet significantly influence the development rate of *T. castaneum*. Certainly, as already hypothesized by Paudyal et al. (2017a), the use of ZeroFly® bags is conditional upon storage of insect-free crops; this may be difficult under farmers' traditional maize production practices, particularly when the use of insecticide is discouraged. Also, long-time exposure of commercially produced insecticide-incorporated bags in the open to alkaline conditions or water, at environmental temperatures >25 °C during marketing or long periods of storage could result in low efficacy, especial if insect-infected grain is stored (NCBI, 2017).

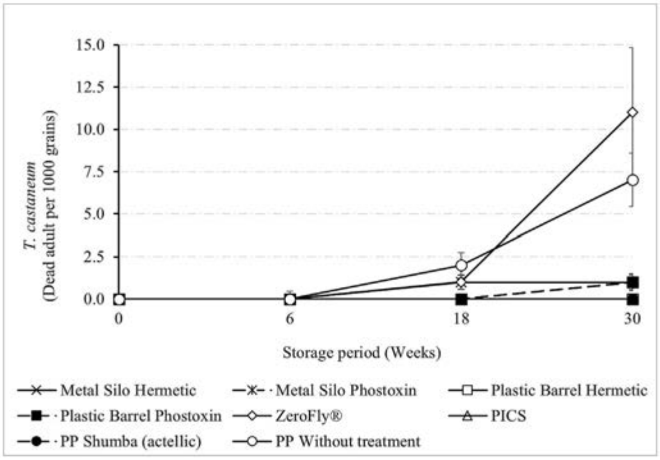

Fig. 6. Number (mean ± SE) of dead *Tribolium castaneum* adult population in the storage technologies over 30 weeks.

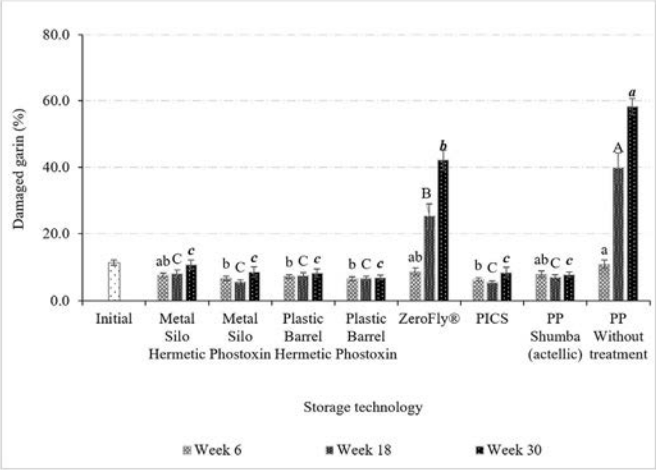

Fig. 7. Percent (±SE) of damaged grains in the storage technologies over 30 weeks. Significant difference between means of damaged grain (%) at Week 6 denoted by different lower case letters (F = 3.17, P = 0.0037), significant difference between means of damaged grain (%) at Week 18 denoted by different upper case letters (F = 25.06, P < 0.0001), significant difference between means of damaged grain (%) at Week 30 denoted by different bold lower case letters in ***italics*** (F = 89.09, P < 0.0001).

3.6. Weight loss (WL)

The consequence of the increase in DG and other factors was that average WL in PP bags (PP without treatment) and ZeroFly® bags continuously increased but did not change significantly in any of the remaining storage treatments (Fig. 8). At week 30 of storage, WL was significantly higher (F = 10.31; $P < 0.0001$) in

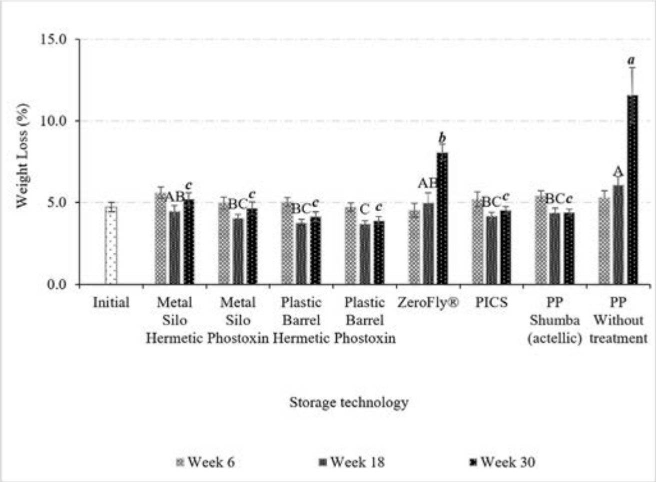

Fig. 8. Percent (±SE) grain weight loss during 30 weeks of storage.
No significant difference between means of weight loss (%) at Week 6 (F = 0.99, P = 0.4379), significant difference between means of weight loss (%) at Week 18 denoted by different upper case letters (F = 3.74, P < 0.0005), significant difference between means of weight loss (%) at Week 30 denoted by different bold lower case letters in ***italics*** (F = 10.31, P < 0.0001).

untreated grain stored in ZeroFly® (8.1 ± 0.6%) and PP bags (11.6 ± 1.7%) than in PP bags with insecticide treatment (PP *Shumba*; 4.4 ± 0.2%). In the other hermetic storage methods with or without insecticide treatment, WL ranged from 3.9 ± 0.2% to 5.2 ± 0.4% without any significant differences among them ($F = 10.3$; $P < 0.0001$), compared to the initial 4.73 ± 0.30% base condition. Thus, there was hardly any WL in PP *Shumba* and the hermetic treatments. These results are consistent with the findings of Afzal et al. (2017) reporting 35% weight reduction in clean uninfected maize seeds stored for eight weeks in PP bags and 3% WL in PICS bags.

The results also suggest that the high WL in PP bags without treatment and ZeroFly® resulted from insect DG to the kernel during storage and that hermetic storage alone was adequate to prevent DG and WL and maintain maize quality. For the current study, we could not deduce a reason for the higher population of live and dead adult *S. zeamais* in ZeroFly® bags than in PP bags without treatment. However, the explanation why grain in PP bags without treatment suffered higher WL than that in ZeroFly® despite the higher insect population could be deduced from the study of Paudyal et al. (2017a) to be a result of the knockdown effect or partial paralysis of the insects by the insecticide in the ZeroFly® yarn. In addition, the initial reduction in DG (at 0–12 weeks) was hypothesized to be due to the storage insects (being both primary and secondary pests of maize) first attacking and feeding on the available DG, reducing the quantity of DG until week 12 (showing a DG reduction), after which they fed on the wholesome grain and so accelerated DG after week 12 of storage. According to Proctor (1994), *S. zeamais* and *T. castaneum* are both primary and secondary pests that feed on grain previously damaged either mechanically or by other insects as much as they feed on whole grain. Hence, kernel breakage (broken grain) resulting from farmers' poor shelling practices may accelerate insect damage during storage as the storage insects attack broken grain first. This explains the decrease in GD and the DG observed as the period of storage was extended. Hence, more labor- and time-saving mechanical shelling methods that will not cause grain breakage could help to reduce insect damage and storage losses. However, the results further indicate that the use of insecticide alone or in combination with hermetic storage could limit the total damage to broken grain.

3.7. *Agents of grain loss*

Considering a batch that was damaged at base condition (before storage), the most critical causes were calculated to be grain breakages (32.2%), fungi infection (31.8%), and damage by insects (24.1%).

A repeated assessment of the stored grain at week 30 of storage, however, showed that the most economically important damage agents were insects, accounting for 25.4% for plastic barrel Phostoxin, 90.8% for ZeroFly®, and 91.4% for PP bags without treatment. (Fig. 9).

Although the absolute values of losses for insecticide-treated or hermetically stored grain were small ranging from 3.9 ± 0.3% for plastic barrel Phostoxin to 5.2 ± 0.4% for metal silo hermetic; fungal coloration appears to constitute an important agent of grain defects in the hermetic containers, accounting for 47.7% of the defects observed in PICS, 39.7% in plastic barrel Phostoxin, and 36.0% in PP *Shumba* (See Supporting File). The increase in moisture in hermetic storage could promote fungi growth. These results corroborate the findings of Tubbs et al. (2016) which concluded that repeatedly opening of PICS bags could promote fungal growth and the risk of aflatoxin contamination, especially with a stored grain of high moisture content. Adams and Schulter (1978) had observed that insect damage by boring within the grain kernels encourages higher moisture in the grain and promotes the development of microorganisms such as fungi.

Due to the small absolute quantities of DG in the hermetic storage treatments (kg per kg stored grain), the absolute amount of fungi spoilage (kg per kg stored grain) would be very small. Nevertheless, precautionary measures are required when using hermetic storage and also with an Actellic application on grain in storage at a commercial scale. Our results suggest a possible change in the performance of hermetic storage containers when grain is stored for long periods (up to 7 months) with regards to moisture uptake by grain, compared with shorter storage periods of time such as 2–3 months (Baoua et al., 2012, 2014; Afzal et al., 2017.)

Correlation analysis associating storage parameters and grain quality indices (Supplementary table) showed that the moisture content of the grain correlated with the prevailing temperature in the storage containers ($r = 0.72$; $P < 0.0001$), especially in airtight storage containers. Also, grain BD had a strong negative correlation with total insect population ($r = -0.75$; $P < 0.0001$) and the extent of DG ($r = -0.80$; $P < 0.0001$). Therefore, insect damage (in the form of holes bored into the grain) resulting from high insect population (Figs. 3 and 5) was the most probable cause of the decrease in BD and high damages of untreated grain stored in ZeroFly® and PP bags that manifested in high WL (Figs. 2, 7 and 8). The high WL indicates possible high food loss during storage. However, there was no correlation between insect population and GM although high moisture content is known to promote the increase of insects and growth of microorganisms in storage (Murdock et al., 2012). It could also be deduced that within the moisture range of the stored grain, grain BD (market quality; Fig. 2) was not influenced by the increase in moisture content of hermetically stored grain nor by the decrease in moisture content of grain stored in non-hermetic conditions (PP Actellic, ZeroFly®, and PP bags).

There was a strong correlation between DG and insect population ($r = 0.97$; $P < 0.0001$). This relationship was expected as a large insect population would cause more damage. Therefore preventing an increase in insect population is a critical factor for reducing DG and WL. In addition, DG was more strongly correlated with the *S. zeamais* population ($r = 0.63$; $P < 0.0001$) than with *T. castaneum* ($r = 0.53$; $P < 0.0001$). Therefore, *S. zeamais* seems to be more economically important in the Central Corridor of Tanzania than *T. castaneum* concerning damage to stored maize grain and food losses. Also, the

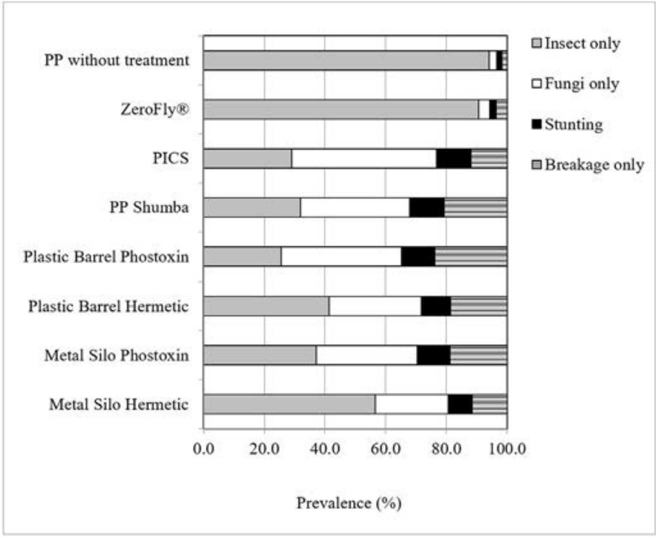

Fig. 9. Percentage contributions of different agents of grain loss.

total insect population was slightly correlated with the humidity of storage treatments ($r = 0.55$; $P < 0.0001$) showing that higher humidity in a storage container may promote an increase in the insect population or vice versa, and thereby increase DG. Unexpectedly, despite the importance of fungi damage in sealed containers, no correlation was established between the amount of grain damaged by fungi and any of the experimental factors.

3.8. Seed germination

Although the storage treatments tested were aimed at the storage of grain rather than seeds, Tanzania farmers have been persistent in their quest to know whether the hermetic storage techniques for grain could also be applied to seed storage.

Germination test results (Fig. 10) showed that at 18 weeks of storage the germination rate was more than 80% regardless of storage treatment and was not significantly different from 92%, the rate obtained before storage. At 30 weeks, germination of grain stored with insecticides or in hermetic storage (68.5 ± 3.6% to 81.4 ± 4.0%) was not significantly different from the 92% germination rate before storage ($F = 15.55$; $P < 0.0001$). Germination rates of grain from plastic barrel hermetic and PP *Shumba* were greater than 80%, the minimum stipulated for commercial seeds, while germination rates of grain stored in ZeroFly® (44.7 ± 4.8%) and PP bags without treatment (37.2 ± 4.0%) were significantly lower ($F = 15.55$; $P < 0.0001$) than those observed in other treatments. It could be concluded that grain germination was significantly affected by storage treatments but up to 30 weeks of storage, there may not be a risk of low germination of grain stored using any of the hermetic storage treatments. Williams et al. (2017) obtained similar results in a laboratory study of maize grain infested with *S. zeamais* and also found that germination rates for grain stored in the insect-infested woven bags were statistically lower than those observed in non-infested woven bags and PICS bags, and concluded that under laboratory test procedures in hermetic storage techniques (triple layer bags) germination of maize was not affected.

3.9. Farmers' perception

Farmers rated the hermetic storage technologies without

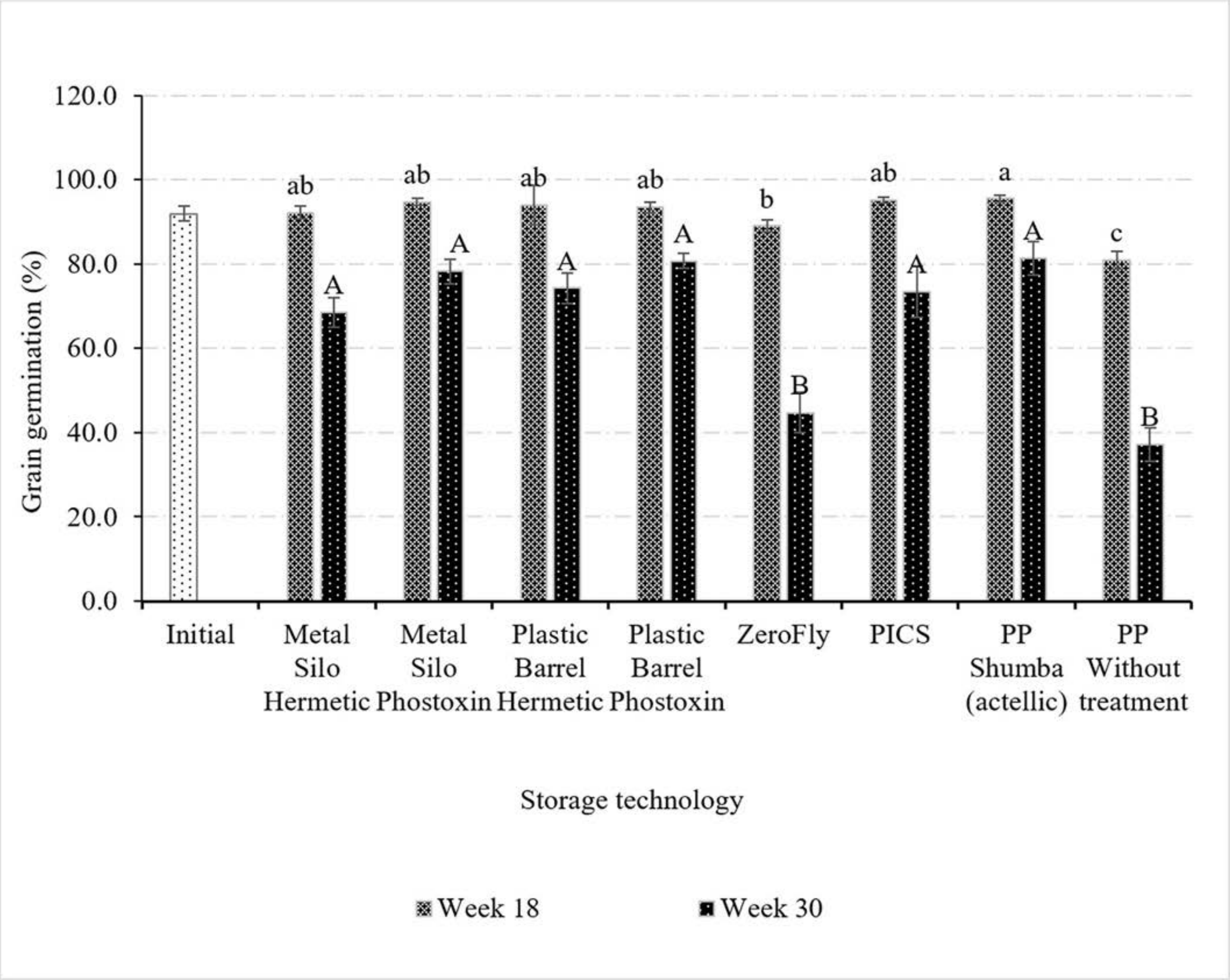

Fig. 10. Percent (±SE) germination of maize grain in the storage technologies over 30 weeks of storage.
Significant difference between means of grain germination (%) at Week 18 denoted by different lower case letters ($F = 10.92$, $P < 0.0001$), significant difference between means of grain germination (%) at Week 30 denoted by different upper case letters ($F = 15.55$, $P < 0.0001$).

insecticide application (metal silo hermetic, plastic barrel hermetic and PICS) as the most effective ways to control storage pests. However, contrary to trial results, PP *Shumba* was not rated as effective. Farmers also liked the same hermetic technologies best. Metal silos were preferred to plastic barrels.

Even though PP bags without treatment did not control storage pests, farmers still liked them as this was a cheap technology. PP *Shumba*, and above all ZeroFly® bags were liked the least. Farmers indicated that the PP *Shumba* treatment was not liked because it altered the taste of the grain. Field observations revealed that farmers who store their maize with insecticide avoid using such grain as much as possible for household consumption but prefer to sell it.

4. Conclusion

This study showed that hermetic storage techniques could be used to store grain for 30 weeks without a significant effect on the quality and germination of the grain. Storage of maize treated with Actellic Super in PP bags, a traditional practice in Tanzania, was effective in controlling insect damage. However, for public health reasons, the application of insecticides to staple food should be avoided especially in locations where trained personnel to supervise the use of insecticides are absent. Hence hermetic storage without the application of insecticides is preferred, but the storage materials need to be made affordable to the smallholders. Sound handling and management of the technologies by farmers must also be ensured, i.e., proper placement and hermetic sealing of lids should be ascertained; insect infestation from the field should be as low as possible; grain must be properly dried before storage, and re-infestation during the intermittent opening of airtight containers should be prevented as much as possible.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jspr.2018.03.002.

Declaration of interest statement

The authors declare that there is no conflict of interest in this manuscript.

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