ISSN: 2456-8643

PERFORMANCE OF DOUBLE AND TRIPLE HERMETIC BAGS FOR MAIZE GRAIN STORAGE

Vedasto Evelius[1], Valerian Silayo[1], and Geoffrey Mrema[1]
[1]Sokoine University of Agriculture, School of Engineering and Technology, P.O. Box 3003, Morogoro, Tanzania

https://doi.org/10.35410/IJAEB.2022.5760

ABSTRACT

A study to compare the effectiveness of two brands of hermetic bags in suppressing maize weevils was carried out at the Department of Crop Science and Horticulture laboratory at SUA for a duration of 180 days. The experiment comprised three treatments: two brands of hermetic bags PICS, AgroZ, and polypropylene bags. The treatments were arranged in a completely randomized design, each replicated three times. Each treatment was artificially infested with maize weevils prior to the experiment setup. Insect count, moisture content, grain damage, weight loss, and germination potential were determined. The AgroZ hermetic bags recorded the lowest weight loss and grain damage mean values of 0.6% and 1.35% respectively. The PICS bag recorded weight loss and grain damage mean values of 0.8% and 0.93% respectively. After 180 days of storage no live insects were found in the maize grain kept in hermetic bags. No significant difference was observed in the effectiveness of hermetic bags. On the other hand, polypropylene bags, had the highest weight loss and grain damage mean values of 8.28% and 24.64%, respectively, as a result of maize weevils. Insect count and germination were significantly different ($P<0.05$) in various treatments. Further research is recommended to be extended into the exploration of the re-usability of locally manufactured hermetic bags.

Keywords: Hermetic Bag Technology, Damaging Storage Insects, Grain Weight Loss, Insect Count, Post-harvest Losses.

1. INTRODUCTION

Maize (*Zea mays L.*) is a major crop grown by the majority of smallholder farmers in most Sub-Saharan African (SSA) countries, providing food and income to millions of people. Tanzania being part of SSA, maize is the most significant food crop, grown on around 45% of the nation's arable land and providing about 100 USD per household annual income in rural areas (Frederick *et al.*, 2020; FAOSTAT, 2021). Despite the significance of maize crops in most households of developing countries, the maize sub-sector is seriously affected by huge post-harvest losses. Overall maize losses in SSA are estimated at 20% compared to 18% in Tanzania (APHLIS, 2020). Postharvest losses have a negative impact on household food, farmer livelihoods, national food security, and income. Lack of access to improved post-harvest storage technologies significantly contributes to losses ranging between 5 and 10% of the total grain losses in SSA (Hodges *et al.*, 2011; Alemu *et al.*, 2021).

Traditional storage techniques used by smallholder farmers remained ineffective against most damaging storage insect pests. Despite the significance of maize products, damaging storage pests are becoming more common, impacting negatively the potential of stored products (Ndegwa *et al.*, 2016). The stored maize is severely affected by the larger grain borer (LGB), *Prostephanus truncatus*, and the maize weevils (*Sitophilus zeamais)* (Holst *et al.,* 2000; Anankware *et al.,* 2012). *Prostephanus truncatus* is a very destructive insect pest that causes significant storage losses, which can exceed 20% within six months of storage (Holst *et al.*, 2000; Tefera, 2012). *Sitophilus zeamais*, on the other hand, can cause weight losses of up to 30% of the entire stored grain weight (Njoroge *et al.,* 2014; Suleiman, 2016). Stored grain losses are significantly associated with the use of unimproved storage systems. Alternatively, farmers decide to employ synthetic insecticides to prevent grain storage losses. However, in some African countries, storage pesticides have been shown to be ineffective against storage insects such as *Sitophilus zeamais* and *Prostephanus truncatus* (Chigoverah and Mvumi, 2016). Furthermore, the use of these insecticides is unsafe for the health of consumers and the environment (Rabé *et al.,* 2021). In order to curb storage losses, farmers opt to sell their harvest as soon as possible after harvest at a very low price and then buy it again at a higher price in the lean season. As this amounts to increased expenditure by farmers, effective and non-chemical methods of grain storage that can substantially reduce the massive grain losses should be identified.

Over the last decade, the use of hermetic storage bags for maize and other grains has been advocated throughout the Sub-Saharan area (Lane and Woloshuk, 2017). The use of hermetic storage bags substitutes traditional storage and the use of synthetic chemicals. The technology works by restricting air and moisture from getting into the grain from outside (Anankware, 2013). The small population of insects already present in the maize consumes the remaining oxygen within the bag once it is filled with the grain, causing them to go dormant and eventually die (Rabé *et al.,* 2021). The hermetic bags brands for instance AgroZ and PICS bags are locally manufactured and commonly available in the local market. The AgroZ bags have two layers; one liner, and one woven bag (90 μm). The liner is co-extruded by mixing HDPE, Metallocene Linear Low-Density Polyethylene (MLLDPE), and oxygen-limiting barrier layers. PICS bags, on the other hand, have triple liners; two ultra-thick (80 μm) high density polyethylene (HDPE) inner liners inserted within a polypropylene outer sack to provide a low permeability seal (Baributsa and Ignacio, 2020). Beginning 2007, the PICS bag, an alternative hermetic storage technology, was introduced in West Africa for the storage of cowpea (Baributsa *et al.,* 2010). Several studies have been undertaken to evaluate the effectiveness of various hermetic bags for grain storage in various countries and areas across the world (Shaw *et al.*, 2020; Ngwenyama *et al.,* 2020). However, there have been few studies that compare the efficiency of various hermetic bags available in the country.

The research by Abass *et al.,* (2017) on on-farm comparison of the effectiveness of hermetic bags with other conventional maize storage technologies, focused on the PICS bag brand only. The study by Chigoverah and Mvumi, (2018) on comparative efficacy of four hermetic bags considered AgroZ under Zimbabwean conditions. Recent research by Kiobia *et al.*, (2020) was on the effectiveness of GrainPro and PICS bags. Additionally, as a result of increased demand among smallholder farmers and private sector investment in the business, additional types of hermetic bags are now becoming commercially available. However, when the private sector's interest in hermetic bags expanded, plastic enterprises entered the market, producing or imitating existing hermetic bags. Because some companies use single or double liners inside the woven bags, the durability of hermetic bags may vary from manufacturer to manufacturer. These factors can have an effect on the performance and reusability of hermetic bags (Baributsa and Ignacio, 2020). Moreover, while prior studies only tested one brand of locally produced hermetic bag, this study compared two brands which are AgroZ and PICS bags. The study focused on the evaluation of the effectiveness of AgroZ and PICS bags in controlling storage insects. The study also seeks to explore the impact of extra inner liner(s) on the effectiveness of hermetic bags. The knowledge and information that will be aggregated will promote technology uptake and serve as a benchmark for policymakers in promoting and disseminating hermetic storage technology.

2. MATERIALS AND METHODS

2.1 Site Description

The experiment was carried out in Morogoro, Tanzania (6° 72' 56" S, 37° 32' 14" E), at the Entomology Laboratory storeroom, Department of Crop Science and Horticulture, Sokoine University of Agriculture. The experimental site was chosen based on the accessibility of the research resources. The experiment was carried out for a period of 180 days from February 2022 to August 2022, under ambient conditions, whereby temperature and relative humidity were 20.1-33°C and 51.9-99.9%, respectively.

2.2 Preparation of Maize Grain and Insects

About 180 kg of fresh maize grain was bought from the contracted farmer to avoid any mixing of different maize varieties. The maize was cleaned, sorted and sun-dried to attain the acceptable storage moisture level of 10.5%. Grain moisture content was measured using a grain moisture meter (*WDN108:-Draminski Electronics in Agriculture, S/N20323*). Neither insecticides nor fumigation were applied to the maize grains prior to loading into the bags. The experimental bags were purchased at random from a local agro-dealer in Morogoro municipality. In addition to that, a sufficient number of *Sitophilus zeamais* were received from the entomology laboratory where they were raised on maize grain at a temperature of 26°C and relative humidity of 65%.

2.3 Treatments and Experimental Procedures

The experiment contained three treatments: two brands of hermetic bags, AgroZ and PICS, as well as a polypropylene bag as the control. The treatments were arranged in a completely randomized design, each replicated three times. Each treatment was loaded with 20 kg of maize and seeded with *Sitophilus zeamais* at the rate of 1 insect per kg of grain *(Likhayo et al., 2018).* The bags were hermetically sealed with ropes after being gently pushed to release the air. All treatments were set on wooden surfaces to avoid moisture absorption from the ground.

2.4 Sampling and Data Collection

After every 30 days for a period of 180 days, each treatment was opened, and about 500 gm of grains were taken from the center and four cardinal points using a 6-slot probe (*Seedburo Equipment Company, Chicago, USA*). The sample was analyzed, and data on the number of live and dead insects; the number of sound and damaged grains; the percentage of germination, and the moisture content of the grain were recorded (Odjo *et al.*, 2020).

2.4.1 Grain Damage, Weight Loss, and Insect Count

The samples were weighed in the laboratory using an electronic balance (*Mettler Toledo, Batch No. PB302*) and sieved with a mesh size of 3 mm to remove insects from maize grains. Manual counts of live and dead insects were recorded and transformed into numbers per kilogram based on a representative sample using a simple proportion (Mlambo *et al.*, 2020). The number of insects from each sample was recorded as either dead or alive. Each sample was poured onto the tray, and the grains were examined for insect damage. The grains in each sample were counted after separating the undamaged from the hole-ridden ones. The weights of the insect damaged grains and undamaged grains were recorded. The Boxall equations (*1* and *2)* were used to calculate the percentage of grain weight loss and grain damage, respectively (Boxall, 1986).

$$\text{Percentage Weight Loss} = \frac{(W_s \times N_d) - (W_d \times N_s)}{W_s \times (N_s + N_d)} x100\% \quad \text{...(1)}$$

$$\text{Percentage Grain Damage} = \frac{N_d}{(N_s + N_d)} x100\% \quad \text{...(2)}$$

where N_d is the number of damaged grains; N_s is the number of sound grains, W_d is the weight of damaged grains, and W_s is the weight of sound grain

2.4.2 Percentage of Germination

From each sample, 100 grains of maize were randomly chosen for conducting germination tests. The grains were planted in trays and watered every day using potable water. On day four and day seven following the seeding the grains that had germinated were counted. The percentage germination was determined as a percentage of the number of germinated grains to the total number of grains sown.

2.4.3 Determination of Moisture Content by Oven Drying Method

Around 200 gm of sub-samples from each treatment was dried at 105°C for 72 hours in an oven (*Memmert UF55 Model 30-750*). After heating, the sub-sample was allowed to cool inside a desiccator, and moisture content (% wet basis) was calculated for each treatment.

2.5 Data Analysis

In MS Excel, data was arranged to compute percentages of grain damage and weight loss using the count and weigh technique. On the other hand, statistical analysis was performed in GenStat 15.1 using an ANOVA. The Tukey honestly significant difference test (Tukey's HSD) was employed to test differences among sample means of significance; and when $P \leq 0.05$, the means are significantly different.

3. RESULTS

3.1 Weight Loss and Grain Damage

There were significant differences (P < 0.05) among the treatments for the mean percentage weight loss and grain damage after 180 days of storage (*Table 1*). Grain kept in PICS bags had the least weight loss and damage followed by grain kept in AgroZ (*Table 1*). The highest mean percentage weight loss recorded for maize stored in polypropylene bags was 15.96% *(Figure 1)* with corresponding 43.53% grain damage *(Figure 2)*.

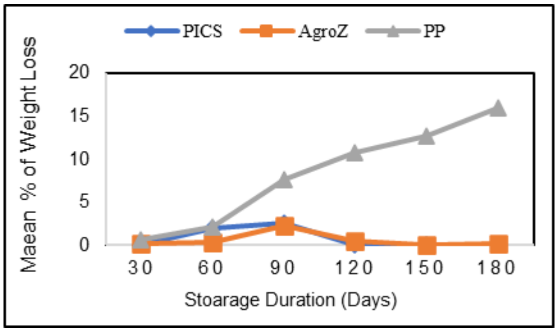

***Figure 1:** A graph showing the weight loss in percentage caused by S. Zeamais*

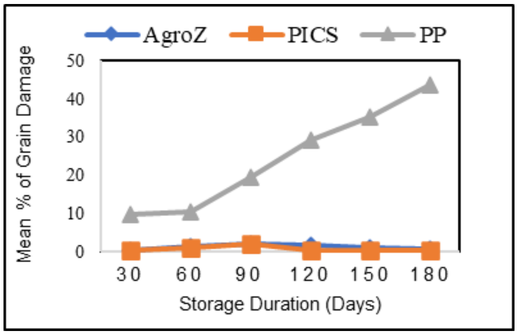

***Figure 2:** A graph showing the grain damage in percentage caused by S. Zeamais*

There was an increasing pattern in weight loss and grain damage over the storage time for all the treatments (Figure 1 and 2). The PICS bags kept the grain safe for 180 days after storage; however, there was a decrease in grain weight loss 90 days after storage but was kept below 2.5% during the 180 days' storage period.

Table 1: Grain damage (%) and weight loss (%) in maize stored for 180 days in hermetic and polypropylene bags infested with *Sitophilus Zeamais*.

Treatments	Grain Damage %	Weight Loss %	Degree of Freedom
AgroZ	1.35[a]	0.60[a]	36
PICS	0.93[a]	0.8[a]	
Polypropylene	24.64[b]	8.28[b]	

Means within a column were compared and separated using Tukey's test at P < 0.05. Means followed by the same letter are not significantly different.

AgroZ brand kept the grain safe during the 180 days of storage, but there was a slight decrease in weight loss after 90 days of storage with damage was kept below 2.3%. A sharp rise in weight loss and grain damage was observed on maize stored in the polyethylene bags, 180 days after storage (*Figure 1and 2*).

3.2 Live and Dead Insect Count

There were significant differences (P < 0.05) between hermetic and polypropylene bags in the mean count of live and dead insects artificially infested *(Table 2)*. The least number of live insects was recorded in grain stored in both brands of hermetic bags (*Figure 3*).

The number of live insects recorded in PICS bags were 27 insects per kg while for AgroZ bag were 36, after 90 days of maize storage (Figure 3), which were the highest. The number of dead

ISSN: 2456-8643

insects recorded in PICS bags were 10 insects per kg while for AgroZ bags were approximately 7 insects per kg after 90 days of storage (Figure 4).

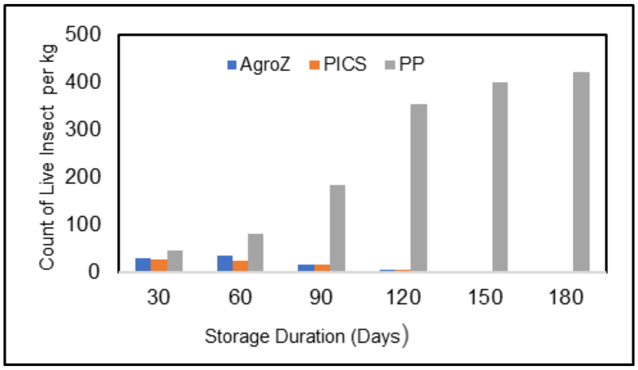

Figure 3: *Mean number of live insects per kg of stored maize grain for six months*

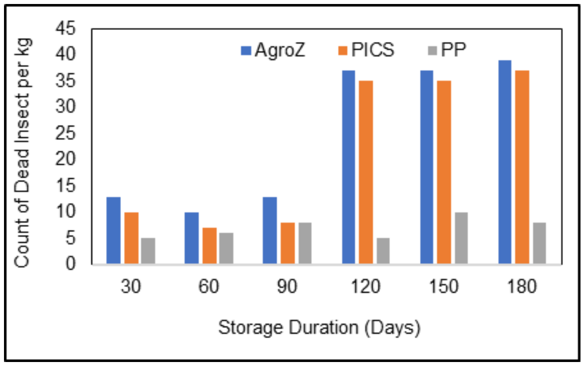

Figure 4: *Mean number of dead insects per kg of stored maize grain for six months*

The highest counts of dead insect for AgroZ and PICS bags after 180 days of storage were around 39 and 37 insects per kg respectively (Figure 4). The number of live insects in polypropylene bag increased sharply after 90 days of storage to 185 insects per kg (Figure 3). The highest record of live insects was for polypropylene bag, which was 422 insects per kg after 180 days of storage.

Table 2: Live and dead insects count in maize stored for 180 days in hermetic bags and polypropylene bags infested with maize weevils.

Treatments	Count of Live Insect per kg	Count of Dead Insect per kg
AgroZ	14.90^{a}	24.73^{b}
PICS	13.26^{a}	22.13^{b}
Polypropylene	248.32^{b}	7.00^{a}

Means within a column are compared and separated using Tukey's test at P < 0.05. Means followed by the same letter are not significantly different.

The lowest count of dead insects in polypropylene bags was 5 at 30 days after storage and the highest was 10 insects per kg recorded after 180 days of maize storage (*Figure 4*).

3.3 Moisture Content

Analysis of variance indicated a significant difference (P<0.05) in the moisture content of maize grain stored in hermetic and polypropylene bags (*Table 3*).

Table 3: Moisture content (%) and germination (%) of maize stored for 180 days in hermetic bags and polypropylene bags infested with *Sitophilus zeamais*.

Treatments	Moisture Content (%)	Germination (%)
AgroZ	10.22^{b}	93.88^{b}
PICS	9.98^{ab}	96.19^{b}
Polypropylene	9.69^{a}	49.09^{a}

Means within a column are compared and separated using Tukey's test at P < 0.05. Means followed by the same letter are not significantly different.

The grains stored in polypropylene bags showed a decrease in grain moisture content over the same storage period, with the final moisture content ranging from 10.5 to 9.43% after 180 days of storage (Figure 5).

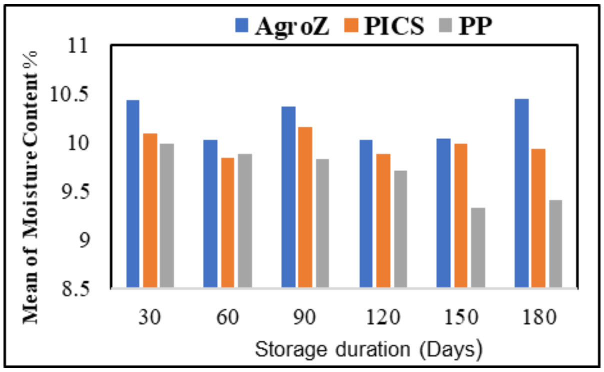

Figure 5*:Moisture content in various storage bags.*

3.4 Germination Percentage

The initial germination for the grain used in this experiment was above 98%. The sharp decline in germination started 60 days after storage in polypropylene bags. However, grain in both the hermetic bags (AgroZ and PICS) maintained germination with minimal progressive decline in the entire 180 days' storage period. The rate of the germination decline corresponds to the increase in the number of damaged grains.

4. DISCUSSION

The study was carried out in a laboratory to simulate actual small scale farmers' grain storage conditions. Prior to the experiment setup about 180 kg of maize grain was purposely infested with maize weevils. Grain damage and weight losses caused by adult weevils' tunneling and feeding significantly increased in the polypropylene bag treatments (0.56–15.96%) as storage time progressed, while decreased in the hermetic bag treatments. The results of this study are consistent with previous research, which found that after seven months of maize storage in polypropylene bags, grain damage and weight loss recorded were 32% and 10.3%, respectively (Baributsa *et al.*, 2020). The study also confirmed that hermetic bags efficiently maintained stored maize while causing the least amount of damage and weight loss. After 180 days, maize grain stored in AgroZ bags had a slightly lower weight loss (0.1-2.3%) than grains stored in PICS bags (0.12-2.5%), indicating no significant difference between these two hermetic brands. The results are also consistent with previous research, which found that the highest weight loss for maize grain kept in hermetic bags ranged between 1% and 3% (Chigoverah and Mvumi, 2018; Abass *et al.*, 2018; Likhayo *et al.*, 2018; Kiobia *et al.*, 2020). However, the massive grain losses observed in polypropylene bags were influenced by climatic circumstances in combination with the ease of air exchange between the stored product environment and the outside environment. In hermetic bags due to their air tightness, resulting in insects' incapacity to live, reproduce, and cause damage and weight loss (Anankware, 2013). Similar results were obtained from the parallel study of PICS and Super Grain bags in Niger (Ngwenyama *et al.*, 2020). The high percentage of grain damage reduces the potential of seed germination.

Among the other indices of concern by the users of hermetic storage bags was seed viability. After six months of storage, hermetic bags effectively maintain grains with an acceptable percentage of germination. After 180 days of maize storage, the AgroZ and PICS bags maintained germination percentages at 99 to 90.7% and 92.5%, respectively. The findings are consistent with previous studies on maize storage in hermetic bags for six months by Chigoverah and Mvumi (2018), which reported germination potential of over 90%. On the other hand, germination percentage of maize stored in polypropylene bag decreased dramatically from 99 to 25%. The findings correspond with other research that indicated polypropylene storage bags lowered the proportion of germination from 76 to 14% after nine months of storage, while hermetic bags maintained germination potential above 85% (Anankware *et al.* 2012). Additionally, the high number of live insect count in polypropylene bags explains the high percentage weight loss, grain damage and low germination power. Therefore, farmers who have limited access to resources to purchase seeds after each planting season can use hermetic bag technology that keep seeds with a high germination rate (Tefera *et al.*, 2018).

The presence of live or dead insects indicates that there were insects with bioactivities that ended their life cycle in the storage. Hermetic bags displayed the fewest live insects in grain during the storage period while grain stored in polypropylene bags had the highest population of insects. This could be due to oxygen depletion in the hermetic bags, caused by the insects' and grain's respiratory activity, which also results in a build-up of carbon dioxide, eventually causing insects' death through suffocation. The results of this study are in line with other research which concluded that hermetic bags were effective in suppressing maize weevils after six months of maize storage (Nganga, *et al.*, 2016; Kiobia *et al.*, 2020; Mompremier *et al.*, 2022). After 180 days of storage, all weevils had died in hermetic bags while there was a very high insect population in the polypropylene bags. As a result, the hermeticity condition completely controlled the insect numbers. However, the unrestricted passage of air between the stored grains environment and the outside atmosphere in the case of polypropylene bags, oxygen is always available for the insects' continued existence and eventual reproduction.

Moisture is among the variables that substantially influence the quality deterioration of stored maize grain. This study indicated that the moisture content of maize grains stored in AgroZ and PICS bags slightly changed over the whole storage period, indicating a lack of oxygen exchanges between hermetic bags and the outside environment. However, the maize grain stored in polypropylene bags significantly lost moisture content. The study findings are in line with previous research that indicated no significant change in the moisture content of maize grain kept in hermetic bags, while it fell dramatically in polypropylene bags (Chigoverah and Mvumi, 2018; Walker *et al.,* 2018; Kiobia *et al.,* 2020; Baributsa *et al.,* 2020).

5. CONCLUSION AND RECOMMENDATION

Storage is the fundamental part of the maize grain post-harvest value chain and is noted as the most critical point of maize losses. The high maize losses in smallholder farming communities are mainly due to inadequate storage facilities. In order to reduce such losses, an effective grain post-harvest storage system should be promoted among smallholder farmers. Hermetic bag technology is cited as an effective method that suppresses grain storage insect pests. The results of this study indicated that AgroZ® and the PICS™ hermetic bags were effective in suppressing weevils. The current study confirmed that hermetic bags are efficient if the stored maize grain is not heavily infested prior to storage. Furthermore, the technology has the potential to considerably minimize post-harvest losses, provided the maize grain is harvested early and dried to the required moisture levels. However, disparities in material properties following an emerging local manufacturer of hermetic bags; for example, PICS bags made of HDPE and AgroZ bags made of MLLDPE materials are possible. As the two materials may have different physicomechanical characteristics, the current work is intended to serve as a starting point for further research into the engineering characterization of materials forming hermetic bags. In light of the current study, further research is recommended to be extended into exploration of the re-usability of the locally manufactured hermetic bags This study also suggests that more research be conducted to investigate the influence of a surge increase in grain storage insect pests on the performance of grain storage systems as a result of climate change.

REFERENCES

Abass, A. B., Fischler, M., Schneider, K., Daudi, S., Gaspar, A., Rüst, J., Kabula, E., Ndunguru, G., Madulu, D., & Msola, D. (2018). On-farm comparison of different postharvest storage technologies in a maize farming system of Tanzania Central Corridor. *Journal of Stored Products Research*, *77*, 55–65. https://doi.org/10.1016/j.jspr.2018.03.002

Alemu, G. T., Nigussie, Z., Haregeweyn, N., Berhanie, Z., Wondimagegnehu, B. A., Ayalew, Z., Molla, D., Okoyo, E. N., & Baributsa, D. (2021). Cost-benefit analysis of on-farm grain storage hermetic bags among small-scale maize growers in northwestern Ethiopia. *Journal of Crop Protection*, *0*(August 2020), 143. https://doi.org/10.1016/j.cropro.2020.105478

Anankware, P. J., Fatunbi, A. O., Afreh-Nuamah, K., Obeng-Ofori, D., & Ansah, A. F. (2012). Efficacy of the Multiple-Layer Hermetic Storage Bag for Biorational Management Of primary Beetle Pests of Stored Maize. Academic Journal of Entomology, 5(5), 47–53. https://doi.org/10.5829/idosi.aje.2012.5.1.61332

Anankware, P. J.. (2013). Triple-Layer Hermetic Storage: A Novel Approach Against *Prostephanus Truncatus* (Horn) Coleoptera: Bostrichidae) and *Sitophilus Zeamais* (Mot)(Coleoptera: Curculionidae). Journal of Entomology, Ornithology and Herpetology: Current Research, 02(03). https://doi.org/10.4172/2161-0983.1000113

APHLIS. (2020). *African Post-Harvest Losses Information System. (2020). Dry weight loss (%): Tanzania - All crops - All years.*

Baributsa, D., Bakoye, O. N., Ibrahim, B., & Murdock, L. L. (2020). Performance of five postharvest storage methods for maize preservation in Northern Benin. *Insects*, *11*(8), 1–12. https://doi.org/10.3390/insects11080541

Baributsa, D., & Concepcion Ignacio, M. C. (2020). *Developments in the use of hermetic bags for grain storage* (Issue July, pp. 171–198). https://doi.org/10.19103/as.2020.0072.06

Boxall, R. A. (1986). A critical review of the methodology for assessing farm-level grain losses after harvest. *Journal of International Biodeterioration,* 25(4), 318–319. https://doi.org/10.1016/0265-3036(89)90010-9.

Chigoverah, A. A., & Mvumi, B. M. (2018). Comparative efficacy of four hermetic bag brands against *Prostephanus truncatus* (Coleoptera: Bostrichidae) in Stored Maize Grain. *Journal of Economic Entomology*, *111*(5), 2467–2475. https://doi.org/10.1093/jee/toy217

Chigoverah, Alex A., & Mvumi, B. M. (2016). Efficacy of metal silos and hermetic bags against stored-maize insect pests under simulated smallholder farmer conditions. *Journal of Stored Products Research*, *69*, 179–189. https://doi.org/10.1016/j.jspr.2016.08.004

ISSN: 2456-8643

FAOSTAT. (2021). World Food and Agriculture – Statistical Yearbook 2021. In *World Food and Agriculture – Statistical Yearbook 2021*. https://doi.org/10.4060/cb4477

Frederick, B., Sabula, L., Mruma, S., Mzee, F., Mtoka, E., Masigo, J., Ndunguru, A., & Swai, E. (2020). *Maize production manual for smallholder farmers in Tanzania*. (p. 32).

Harvest, G. for A. on S. R. to G. after. (1998). *Technical Leaflet No. 1 Larger grain borer*. CTA, 380 Postbus 6700 A J Wagenigen The Nerthalands.

Hodges, R. J., Buzby, J. C., & Bennett, B. (2011). Postharvest losses and waste in developed and less developed countries: Opportunities to improve resource use. *Journal of Agricultural Science*, *149*(S1), 37–45. https://doi.org/10.1017/S0021859610000936

Holst, N., Meikle, W. G., & Markham, R. H. (2000). Grain injury models for *Prostephanus truncatus* (coleoptera: bostrichidae) and *Sitophilus zeamais* (coleoptera: curculionidae) in rural maize stores in West Africa. *Journal of Economic Entomology*, 93(4), 1338–1346. https://doi.org/10.1603/0022-0493-93.4.1338

Kiobia, D. O., Silayo, V. C. K., Mutabazi, K. D., Graef, F., & Mourice, S. K. (2020). Performance of hermetic storage bags for maize grains under farmer-managed conditions: Good practice versus local reality. *Journal of Stored Products Research*, *87*, 101586. https://doi.org/10.1016/j.jspr.2020.101586

Lane, B., & Woloshuk, C. (2017). Impact of storage environment on the efficacy of hermetic storage bags. *Journal of Stored Products Research*, *72*, 83–89. https://doi.org/10.1016/j.jspr.2017.03.008

Likhayo, P., Bruce, A. Y., Tefera, T., & Mueke, J. (2018). Maize grain stored in hermetic bags: Effect of moisture and pest infestation on grain quality. *Journal of Food Quality*, *2018*. https://doi.org/10.1155/2018/2515698

Mompremier, R., Bern, C., Bowers, E., Brumm, T., & Maier, D. (2022). Field testing of Purdue improved crop storage (PICS) bag maize storage in Haiti. *Journal of Stored Products and Postharvest Research*, *13*(June), 1–5. https://doi.org/10.5897/JSPPR2021.0323

Shaw Mlambo, Brighton M. Mvumi, Tanya Stathers, Macdonald Mubayiwa, T. N. (2020). Field efficacy of hermetic and other maize grain storage options under smallholder farmer management. *Journal of Crop Protection*, 274–282. https://doi.org/10.1016/j.cropro.2017.04.001

Ndegwa, M. K., De Groote, H., Gitonga, Z. M., & Bruce, A. Y. (2016). Effectiveness and economics of hermetic bags for maize storage: Results of a randomized controlled trial in Kenya. *Journal of Crop Protection*, *90*, 17–26. https://doi.org/10.1016/j.cropro.2016.08.007

Nganga, J.; Mutungi, C.; Imathiu, S.; Affognon, H. (2016). Effect of triple-layer hermetic bagging on mould infection and aflatoxin contamination of maize during multi-month on-farm storage in Kenya. *J. Stored Prod. Res.*, *69*, 119–128.

Ngwenyama, P., Mvumi, B. M., Nyanga, L. K., Stathers, T. E., & Siziba, S. (2020). Comparative performance of five hermetic bag brands during on-farm smallholder cowpea (Vigna unguiculata L.Walp) storage. *Journal of Stored Products Research*, *88*, 101658. https://doi.org/10.1016/j.jspr.2020.101658

Njoroge, A. W., Affognon, H. D., Mutungi, C. M., Manono, J., Lamuka, P. O., & Murdock, L. L. (2014). Triple bag hermetic storage delivers a lethal punch to *Prostephanus truncatus*

(Horn) (Coleoptera: Bostrichidae) in stored maize. *Journal of Stored Products Research*, *58*, 12–19. https://doi.org/10.1016/j.jspr.2014.02.005

Odjo, S., Burgueño, J., Rivers, A., & Verhulst, N. (2020). Hermetic storage technologies reduce maize pest damage in smallholder farming systems in Mexico. *Journal of Stored Products Research*, *88*, 2–10. https://doi.org/10.1016/j.jspr.2020.101664

Rabé, M. M., Baoua, I. B., & Baributsa, D. (2021). Adoption and profitability of the purdue improved crop storage technology for grain storage in the south-central regions of Niger. *Agronomy*, *11*(12). https://doi.org/10.3390/agronomy11122470

Shaw Mlambo, Brighton M. Mvumi, Tanya Stathers, Macdonald Mubayiwa, T. N. (2020). Field efficacy of hermetic and other maize grain storage options under smallholder farmer management. *Crop Protection*, 274–282. https://doi.org/10.1016/j.cropro.2017.04.001

Suleiman, R. A. (2016). *Assessing and Controlling Bio-deterioration of maize in Tanzania (PhD Dissertation, Iowa State University)* [Iowa State University]. https://lib.dr.iastate.edu/etd/15817

Tefera, T., Teshome, A., & Singano, C. (2018). Effectiveness of Improved Hermetic Storage Structures Against Maize Storage Insect Pests *Sitophilus zeamais* and *Prostephanus truncatus*. *Journal of Agricultural Science*, *10*(8), 100. https://doi.org/10.5539/jas.v10n8p100

Walker, S., Jaime, R., Kagot, V., & Probst, C. (2018). Comparative effects of hermetic and traditional storage devices on maize grain: Mycotoxin development, insect infestation and grain quality. *Journal of Stored Products Research*, *77*, 34–44. https://doi.org/10.1016/j.jspr.2018.02.002