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Evaluation of Hermetic Maize Storage for Smallholder Farmers

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Abstract.
Maize is an important crop for many smallholder farmers in the world. Maize weevils (Sitophilus zeamais) cause a significant loss in quality and quantity during maize storage in tropical regions. Hermetic storage of maize has been shown to be effective in controlling maize weevils in laboratory settings. The objective of this research was to test the effectiveness of hermetic storage containers that could be used by smallholder farmers. Six 208-L (55-gallon) steel barrels were filled with 170 kg (375 lb) of maize with initial weevil populations of 25 live weevils/kg of maize (11 live weevils/lb). The barrels were placed in a room at 27^{0}C (81^{0}F) under non-hermetic condition for three weevil lifecycles of approximately 40 days each. After 120 days, the weevil population increased to an average of 99 live weevils/kg (45 live weevils/lb). Three barrels were then hermetically sealed. After storage for 21 days, the weevil population was zero live weevils/kg in the hermetically sealed barrels (100% mortality) and an average of 214 live weevils/kg (98 live weevils/lb) in the non-hermetic barrels. Means of barrel oxygen content, ending number of live weevils per kg of maize, test weight (TW), moisture content (MC), temperature and humidity were significantly different between the hermetic and non-hermetic storage treatments. Broken corn and foreign material (BCFM) and mechanical damage (MD) were not significantly different. Hermetically sealed metal barrels for maize storage can control maize weevils and may be an effective storage option for smallholder farmers.

Keywords: *Maize weevil, tropical regions, maize storage, test weight, BCFM, mechanical damage, moisture content*

Introduction

Maize (*Zea mays)* is a major staple crop for smallholder farmers with over 300 million consumers in Africa (Daily Guide, 2010). In 2011, maize was harvested on 170 million ha worldwide resulting in 883 million Mg of production (FAOSTAT, 2014). By 2025, maize will be the most highly produced crop both globally and in

developing countries (CIMMYT and IITA, 2011; Rosegrant et al., 2008).
The maize weevil (*Sitophilus zeamais*) is a major pest of maize during the drying and storage periods of production especially in tropical and sub-tropical regions. It is approximately 2.5 to 4 mm long with a brown color (Fig 1) and an average lifecycle of 36 days (Khare, 1994). Maize weevils can be extremely destructive to stored maize. The female weevil bores through the pericarp of mostly undamaged kernels and deposits an eggs into the intact inner portion of the kernel which is then sealed off by a mucus like substance. The pupa consumes the inner portion of the kernel. After emergence from the pupae, the adult weevils damage grain by feeding on the endosperm or starchy areas of the grain kernel plus chewing the outer layer of the grain to make a hole of roughly 1.5 mm in diameter (Kranz et al., 1997). Up to 50% loss of maize can occur due to weevils during storage (Boxall, 2001). Damage inflicted on the kernels also provides potential openings for disease and fungal growth in the grain (CGC, 2013).

Figure 1: Maize weevils on maize and emergence holes (CGC, 2013)

Hermetic storage of maize depletes oxygen and increases carbon-dioxide inside a storage system due to respiration of stored products and other living organisms (i.e., weevils) through sealing which prevents interaction with the outside environment. When oxygen levels fall below about 5%, insect activity ceases and insects die (Gummert et al., 2004).

Previous research studied the effects temperature, time, maize moisture and oxygen levels on maize weevil mortality (Yakubu et al., 2011). Weevil infested commercial hybrid maize grain samples in 476-mL (1 pint) jars were held under hermetic conditions at maize moisture levels of 6.3% and 16% w.b., and at two levels of temperature, 10^0C and 27^0C. The hermetic conditions were effective in killing weevils. There were significant effects due to temperature and moisture content. Equations were developed to predict the time to 100% adult weevil mortality as a function of temperature, maize moisture content and initial oxygen volume.

Other hermetic storage systems in use include double and triple plastic bags (Baoua et al., 2013; Murdock and Baoua, 2014; Murdock et al., 2012), which are being used to store cowpeas in west Africa. This technology requires substantial operational involvement and associated skill to achieve air-tightness. Experience may be necessary to achieve good results and hermetic conditions are not guaranteed. It is difficult to maintain a sealed system for a long period of time, and molding of grain can occur where moisture has accumulated in the storage bags (Caddick, 2007). While bagging may be to some extent effective in killing insects, it doesn't provide mechanical protection against rodents and the bag usually has no more than two years of useful life (C. J. Bern et al., 2013). Barrels provide that mechanical protection and are of a size useful to many smallholder farmers. They can be fabricated from locally available materials like galvanized steel sheets, washable barrels previously used for the storage of other products and their construction by local artisans creates jobs. A good example is the postcosecha which is built from 26-gauge (0.7-mm) galvanized steel sheets and lead based solder. A 5-mm fold is formed to make the joints and seams which are the crimpled and soldered (C. J. Bern et al., 2013).

In practice, larger containers (e.g., drums or barrels) can be used for hermetic maize storage. However, the hermetic efficacies of larger volume containers have not been demonstrated. The objective of this research was to evaluate the effectiveness of 208-L (55-gallon) steel barrels for hermetic maize storage.

Material and methods

Containers

Six 208-L (55-gallon) open head, unlined, steel barrels (Sioux Chief Mfg Co. Model 882-35, 24110 S Peculiar Dr, Peculiar, MO 64078) were used as storage containers. The barrels could be covered either with: (1) screens to retain weevils but yet allow for air passage (long ultra-sun block solar screens, New York Wire, Mt. Wolf, PA); (2) or hermetically sealed lids from the Sukup Food Storage System (Sukup Manufacturing Co. Sheffield, IA). Before cleansing, all barrels were filled with warm water and turned upside down to check for water leaks. They were then cleansed with Ajax triple action liquid soap, a large cotton mop and a medium handle brush with warm water. After thorough rinsing, the barrels were left to dry.

Weevils

Weevil infested commercially comingled maize was used as the source of maize weevils. Weevils were separated from the maize by passing the infested maize through a Carter Day Dockage tester (CEA, Minneapolis, Minnesota 55432 USA) with 4.76-mm (12/64-inch) screen to retain the maize and a 0.99-mm (2.5/64-inch) screen to retain the weevils plus some small broken maize kernels. Three representative samples of weevils were used to determine a weight of 36.72 g per 1,000 weevils. Weevil quantities for seeding the barrels were determined by weight rather than counting.

Maize

The six barrels were each loaded with 170 kg (375 lb.) of weevil-free commercial comingled bulk maize from the 2012 harvest. The maize had an average a moisture content of 13.4%. Each barrel was seeded with live weevils at a rate of 25 live weevils/kg of maize (time T = 0 days) and covered with a screen to prevent weevil migration. The loaded barrels were held in a room maintained at 27 ± 2^0C with fluorescent lights on. After 120 days (T = 120, approximately three weevil life cycles), representative samples from each barrel showed an average weevil population of 99 live weevils/kg. Three barrels were randomly selected and sealed with hermetic lids equipped with oxygen sensors while the other three remained covered with screens. At T=122 days, the hermetic barrels were unsealed due to suspected malfunction in the oxygen monitoring sensors. The hermetic barrels were resealed at T= 129 days until T = 150 days when they were unsealed and all barrels were sampled. From T = 151 days to T = 190 days, the previously hermetically seals barrels were covered with screens to determine if there was adult weevil development from previous eggs, larva or pupae.

Measurements

Representative samples of the maize were taken at different times using a sampling probe inserted three times into each barrel at different angles. Weevil mortality was determined (Gullan and Cranston, 2010; Yakubu et al., 2010). Samples were analyzed for broken corn and foreign material (BCFM) (Krueger et al., 2007), moisture content (ASABE, 2006), test weight (TW) (USDA, 1996) and mechanical damage (MD) (Steele, 1967). Oxygen content inside the hermetically sealed barrels was determined using oxygen sensors (Model 65, AMI, Huntington Beach, CA) connected to a computer via a PMD 1408FS DAC system. Aflatoxin analysis was performed at the end of the experiment using Charm ROSA-M reader which uses lateral flow strips. It detects the sum of aflatoxins B1, B2, G1, and G2. The extraction was done with 70% methanol, which is what was required for these particular lateral flow test strips. Temperature and relative humidity readings inside barrels was collected using haxo-8 temperature and humidity logger (879 Maple Street Contoocook, NH 03229 U.S.)

inserted in each barrel at either top, middle, or bottom. The resulting data were analyzed using JMP Pro 10 and Microsoft Excel.

Results and discussion

Broken corn and foreign material (BCFM)

There was a general increase in the BCFM in all the six barrels from 1.6% to 3.14% on average from time, T = 0 to 150 days and then there was a slight decline to 2.33% from T = 150 to T = 190 days (Fig 2). The BCFM results were not significantly different among barrels during the time under which weevils went through several lifecycles (p=0.9295) and the time of hermetic verses non-hermetic treatments (at T = 122 days, p=0.2851 and at T= 150 days, p=0.5888 CI=95%) (Table 1). At T=190 days, BCFM results were not significantly different between previously hermetically sealed and non-hermetic barrels (p=0.8112). The increase in the BCFM was attributed to the increased number of maize weevils in the barrels while the decline was attributed to possible sampling error. BCFM absorbs moisture more rapidly than grain (Navarro, 2006). This favors mold development, a condition which was observed on maize and fines close to barrel sidewalls.

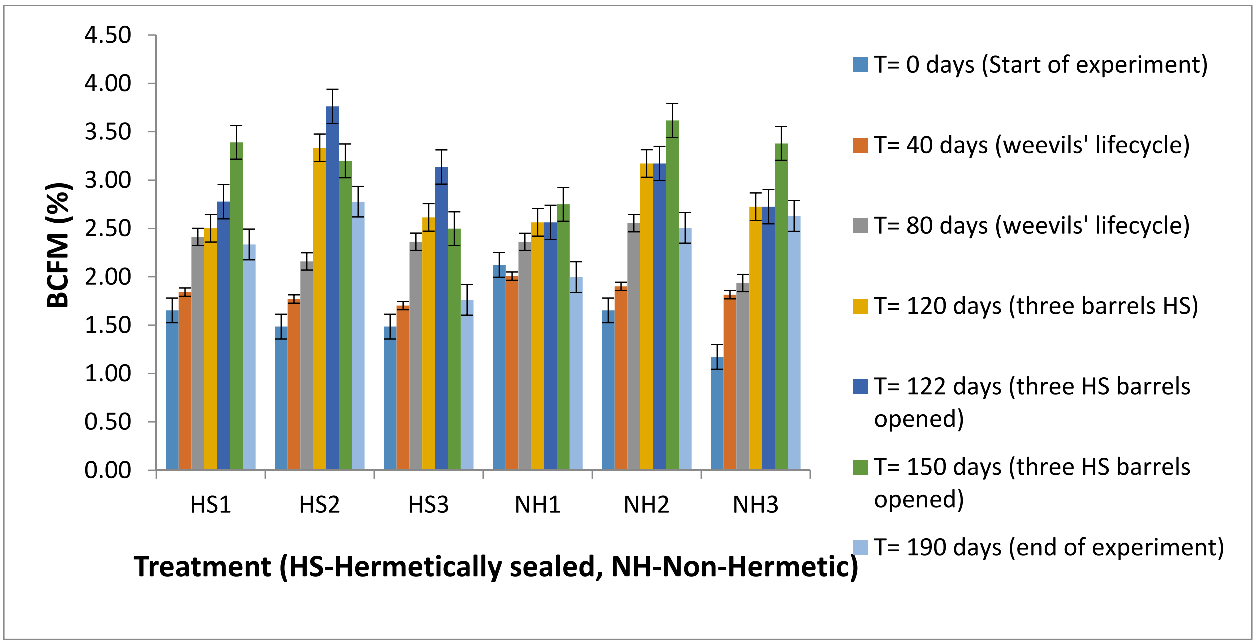

Figure 2: Mean BCFM results at different treatments and time periods.

Maize moisture content (MC)

Maize moisture ranged from 13.7% to 12.5% during the 190 days of the experiment with a general increase for 40 days and a decline after that (Fig 3). Maize moistures in all barrels during population increase (T = 0 to T=120) were not significantly different (p= 0.5999). Moisture differences between hermetically sealed and non-hermetic barrels were not significant (p=0.5772) after one day of sealing and there was a significant difference between hermetically sealed and non-hermetic barrels after resealing, T =150 days (p=0.0488, R^2=66.2%) (Table 1). At T=190 days, moisture was not significantly different between barrels (p=0.3092). The increase in moisture during the first 40 days was probably due to the respiration of maize and weevils. The decline would have perhaps been due to maize establishing equilibrium moisture. Under this process moisture is assumed to have moved to the sides of the barrels to where the probe could not get samples. This assumption is supported with the observation of mold and/or deteriorated corn which was on barrel walls. Metal silos have a disadvantage of moisture migration and condensation in hot climates and this may limit hermetic storage (Navarro, 2006).

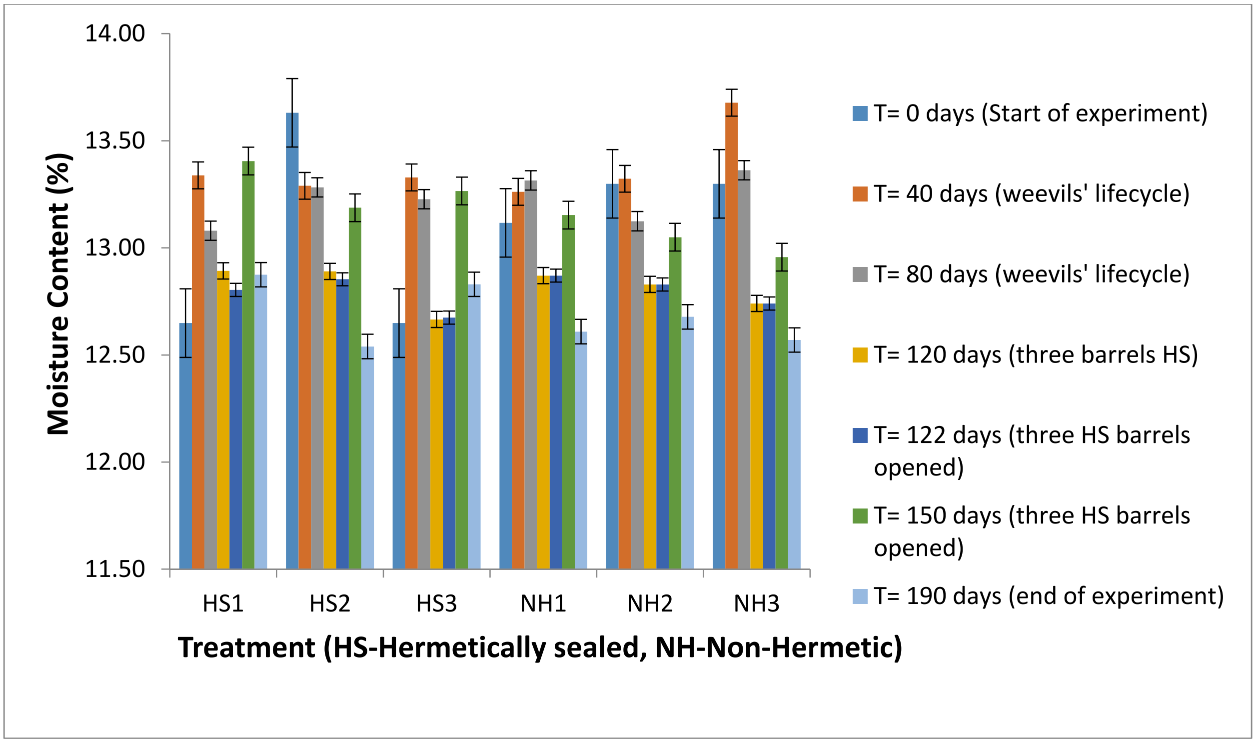

Figure 3: Mean moisture content results at different treatments and time periods.

Test weight (TW)

There was a decline in TW from 739 to 705 kg/m^3 (57.4 to 54.8 Ib/bu) on average during the experiment (Fig 4). During the first 120 days, TW difference was not significant between treatments (p = 0.9987). After one day of sealing, the TW difference was not significant between hermetic and non-hermetic barrels (p=0.8203) but after complete resealing (T=150 days), TW was significantly different (p=0.0194, R^2=78.12%) (Table 1). At T=190 days, TW was significantly different between the previously hermetic and non-hermetic barrels (p=0.0048 and R^2=88.89%) (Table 1). As the maize was losing moisture, there was an expected increase in TW (Bern and Brumm, 2009) but the declining TW can be attributed to immature corn and/or a change in the dry material quantity or deterioration that could have occurred due to infestation of the maize by weevils (Bern and Brumm, 2009).

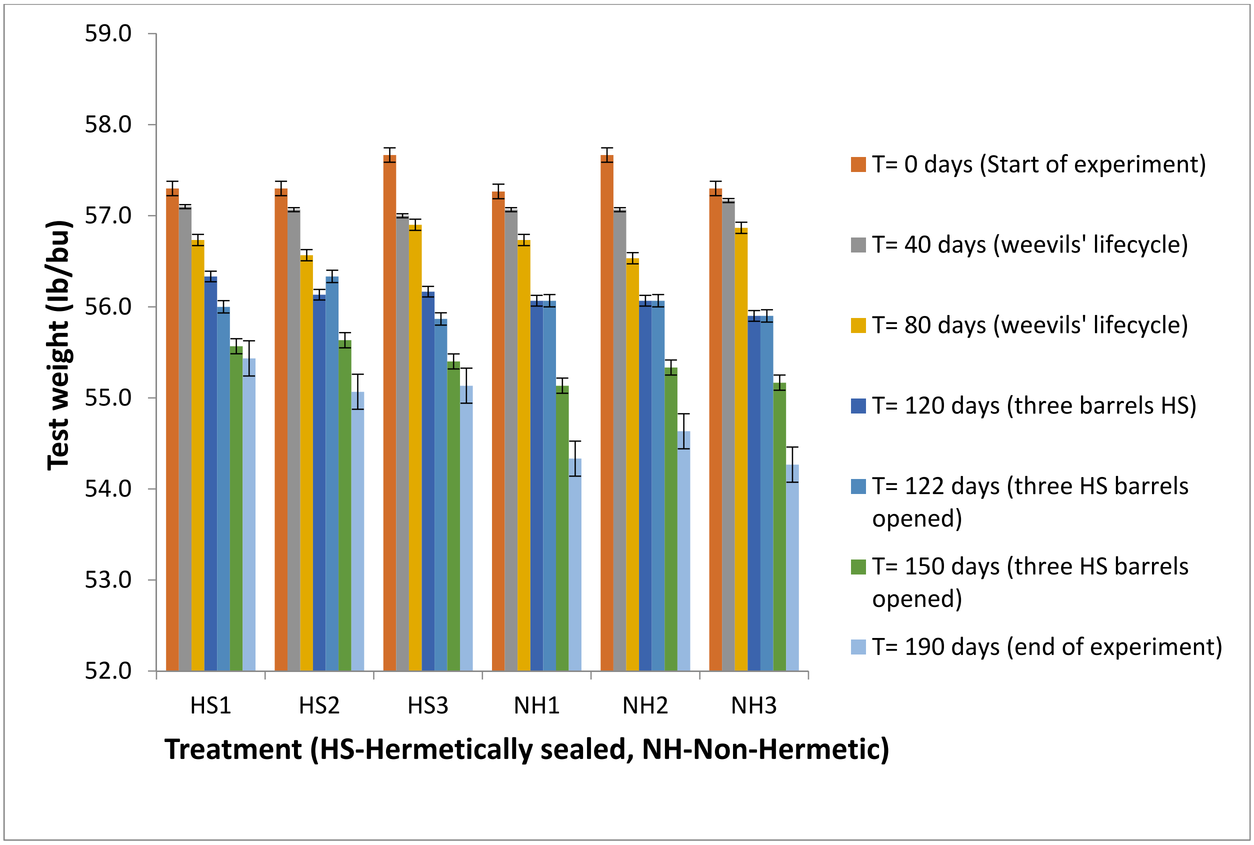

Figure 4: Mean test Weight (TW) at different treatments and time periods.

Mechanical Damage (MD)

MD is the percentage by weight of kernels with a missing portion or any visible crack or rupture of the seed coat (Steele, 1967). There was a general increasing trend from 4.34% to 8.43% on average in all treatments (Fig 5). The MD differences were not significant between all barrels during weevil population growth up to 120 days (p = 0.3784). It was also not significant between hermetically sealed and non-hermetic barrels after one day of sealing i.e. T =122 days (p = 0.2769) and after complete resealing T=150 days (p = 0.0642). However, MD was significantly different between previously hermetically sealed and non-hermetic barrels at T= 190 days (p = 0.0349) (Table 1). The increase in MD was probably attributed to the increasing number of weevils in the barrels. The significant difference at the end of the experiment was due perhaps to no weevils in the previously hermetically sealed barrels compared to non-hermetic barrels which had an increasing number of weevils. The results were in line as those observed by Foster et al., 1955 in which damaged kernel numbers varied considerably throughout the experiment.

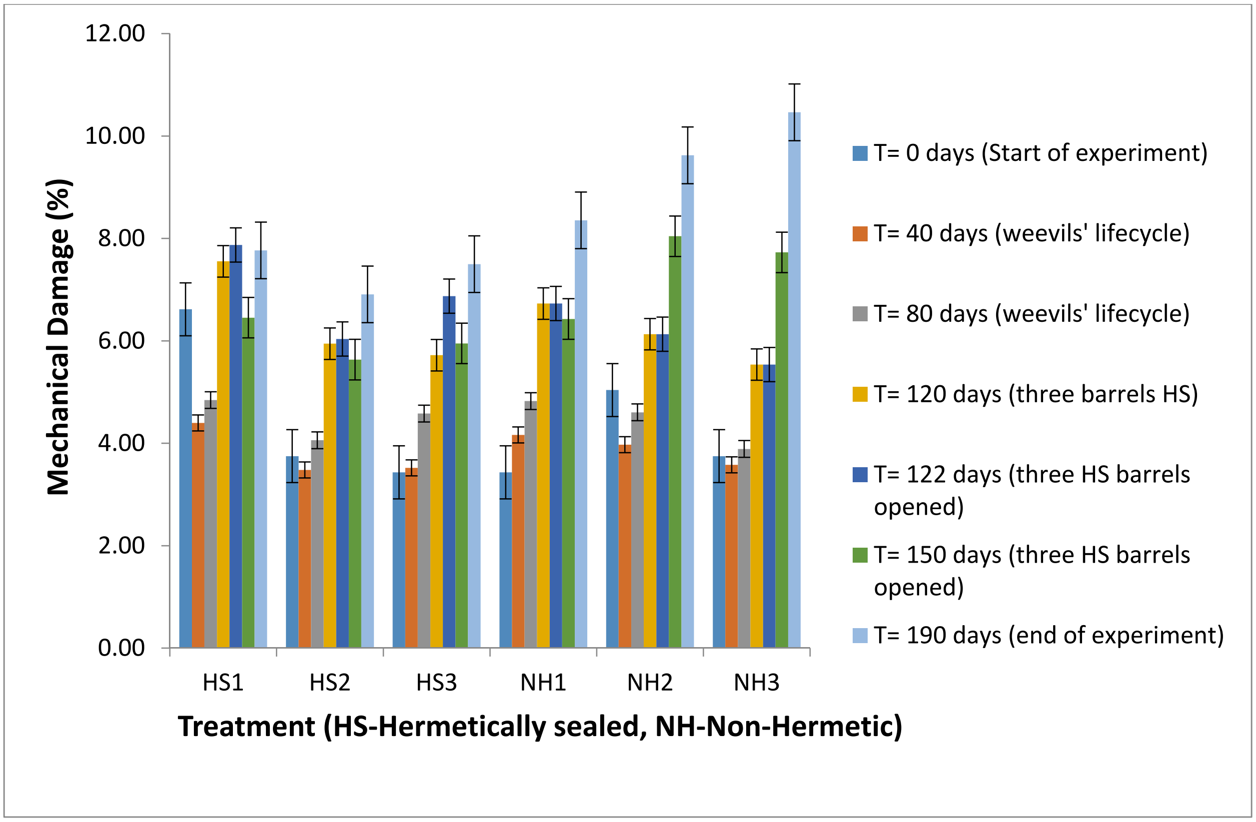

Figure 5: Mean mechanical damage at different treatments and time periods.

Weevil Mortality

From time, T = 0 to T= 120 days, the weevils were left to go through several lifecycles so as to increase in population density. The target was to have 100 weevils/kg of corn. The initial population density was 25 weevils/kg of corn and after 120 days, it was 99 weevils/kg on average. After one day of sealing (T=121 days), the oxygen levels dropped below 4% on average. The three hermetic barrels were then unsealed due to suspected malfunctioning of the oxygen sensors. Upon unsealing, weevils were seen to have accumulated mostly on top of the maize, on the sides of the barrels, below the oxygen sensor and under the lid. After 24 h (T=122 days) of exposure to oxygen with a screen on top, the barrels were sampled. Live weevils dropped from 99 weevils/kg to 17 weevils/kg on average. This meant that though all weevils seemed to be all dead by visual observation, some were just dormant and after exposure to oxygen, they became active again. This could have been a narcotic effect of carbon dioxide leading to immobilization and/or knock-down of weevils (Aliniazee, 1971; Edwards and Rollas, 1973; Navarro, 2006) The calculated expected mortality days for 99 weevils/kg was 8 days (Yakubu et al., 2011). The three barrels (HS1, HS2 and HS3) were left unsealed for 7 days (from T =122 to T= 129) but with a screen on top to prevent escape of live weevils. At T= 129 days, barrels HS1, HS2 and HS3 were resealed again. The calculated time to mortality for 17 weevils/kg was 20 days. After 20 days (T=149 days), the same observations were seen as those observed after one day of sealing. Weevils were exposed to oxygen for 24 h (T = 150 days). After 24 hours, barrels were sampled and the population density was 0 weevils/kg on average. From T= 150 to T= 190 days, all the six barrels were left with a screen on top to prevent escape of weevils. The purpose for this time period was to investigate if the hermetic storage had an effect on other life stages of maize weevils, that is to say eggs, larva and pupa.

Figure 6 shows the number of weevils (live weevils/kg maize) as a function of time for the hermetically and non-hermetic barrels. At the time of hermetic sealing (T=120 days), the six barrels averaged 99 live weevils/kg. The number of live weevils was not significantly different among barrels for the first 120 days ($p = 0.9581$).There was an increase of weevils in the non-hermetic barrels up to 214 weevils/kg while the hermetically sealed barrels' weevils declined to 0 weevils/kg at T=190 days (Fig 2). There was significant difference between hermetic and non-hermetic barrels after one day of sealing ($p = 0.0060$, R^2=87.61%), after complete sealing, T =150 days ($p = 0.0011$, R^2=94.68%) and at T= 190 days ($p = 0.0002$, R^2=97.60%) (Table 1). A 95% confidence interval was considered. The decline (T =40 days) was attributed to the weevils not yet being adapted to the new environment or probably some of them were nearing the end of their lifecycle. The population increase in the non-hermetic barrels was because of the favorable maize moisture and temperature (Sone, 2000) and the complete mortality in hermetically sealed barrels was because of oxygen depletion and CO_2 enrichment (Anankware et al., 2013; Anankware and Bonu-Ire, 2013; Fleurat, 1990; Foster et al., 1955; Navarro, 2006; Navarro et al., 1990; Oxley and Wickenden, 1963; Villers et al., 2010; Yakubu et al., 2011, 2010).

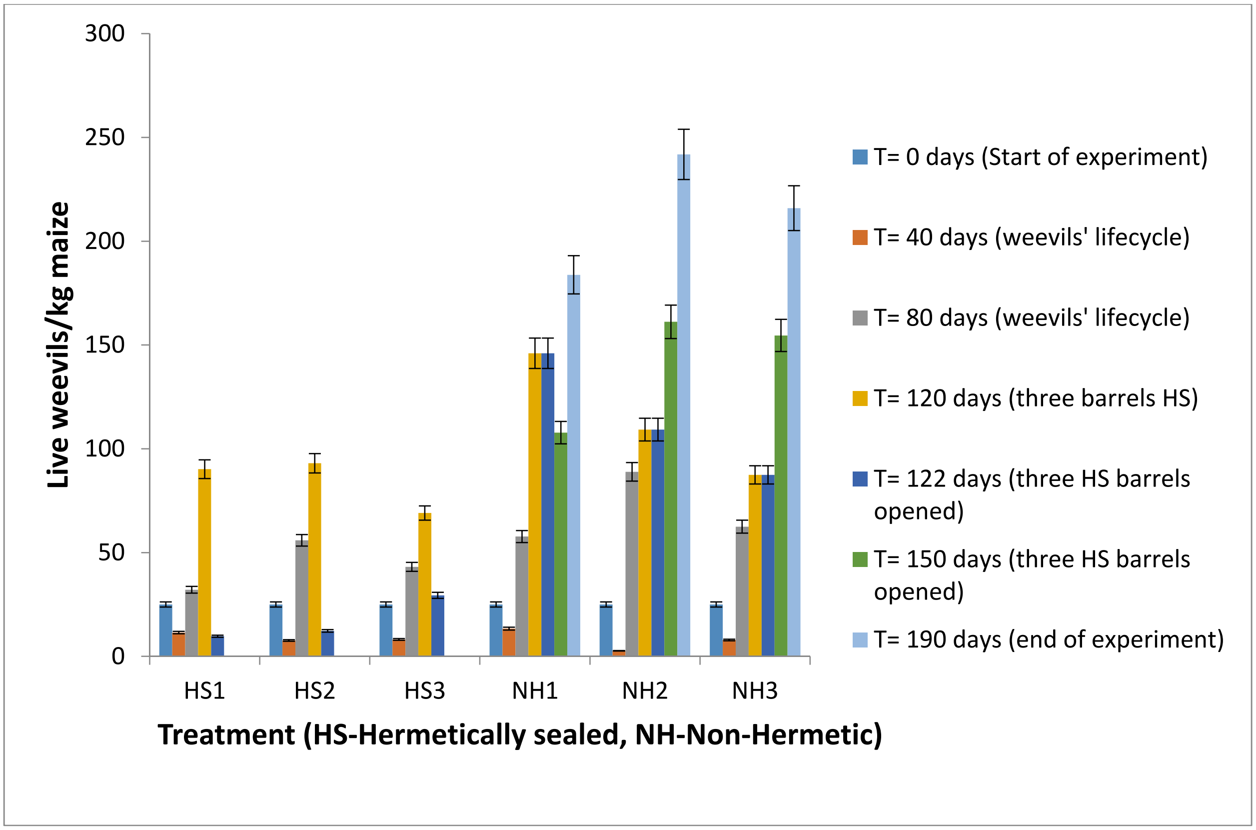

Figure 6: Mean live weevils/kg of maize at different treatments and time periods.

Oxygen sensor readings for HS1, HS2 and HS3 (T=120-122 days)

There was a general decline in the percentage oxygen in the three sealed barrels from 23% to 3% on average by 120.2 days. Then the oxygen values increased to 6.7% from the 120.2-120.4 days and finally there was a decline to a constant value of 5.5% on average up to 120.8 days (Fig 7). Oxygen levels inside the sealed barrels was significantly different from the atmospheric oxygen level ($p = 0.0027$).

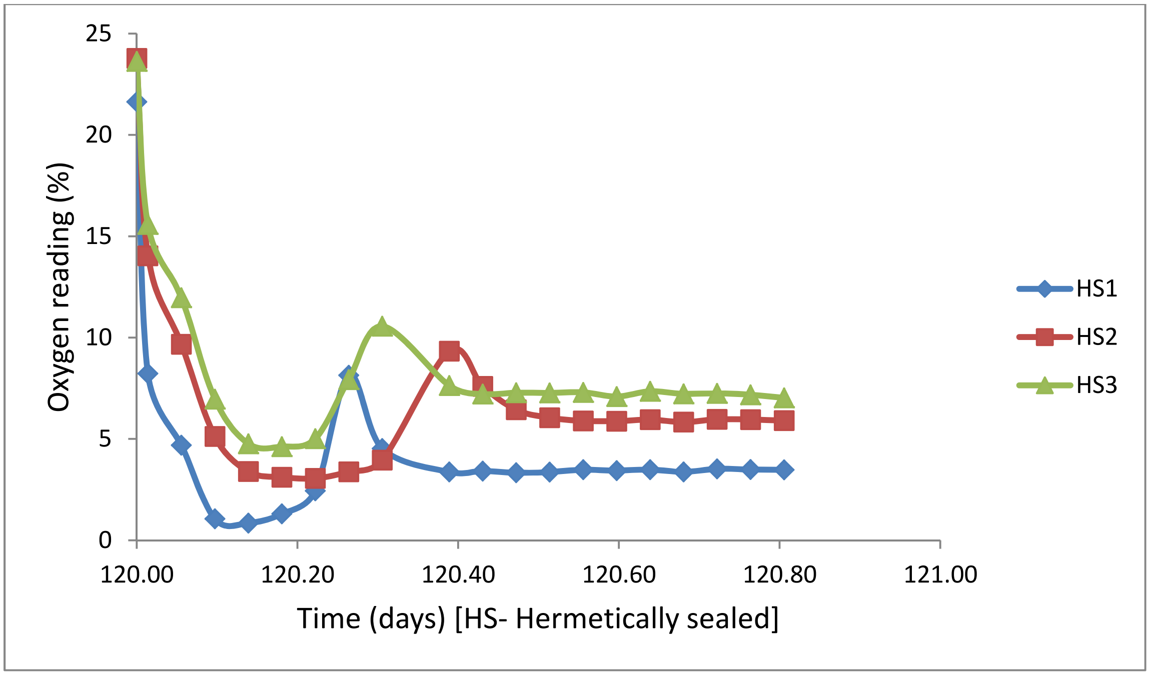

Figure 7: Oxygen content inside hermetically sealed barrels (T=120-122 days)

Oxygen sensor readings for HS1, HS2 and HS3 (T=129-150 days)

After resealing the barrels, the curve followed almost the same trend as the curve obtained after T=120-122 days of sealing (Fig 7) with a decline to below 5% at T=129.2 days and then, after a rise of between 5 and 10 percentage points oxygen, a decline to a constant value (Fig 8). Oxygen readings remained constant in all the three hermetic barrels HS1, HS2 and HS3 from T=130.4 days until the end of the experiment (T=149 days). This portion is not shown on Fig 8. Oxygen level inside the sealed barrels was significantly different from the atmospheric oxygen level ($p < 0.0001$). The decline in oxygen with time was expected; however the slight increase between 129.25 and 129.5 days and a quick decline in oxygen before the expected calculated oxygen consumption days were unexpected. The trend was similar to that observed by Villers et al., 2010 though with lower fluctuations while studying hermetic storage of cocoa beans. Generally, to some extent the results do not agree with the oxygen levels of <3% recommended for complete mortality by Banks and Annis, 1990; Fleurat, 1990; and Navarro, 1978 for effective control. However 100% mortality rate was achieved. Bailey, 1955, 1956, 1957, 1965 suppressed storage insects at about 5% oxygen with longer exposure time, which is almost the same concentration observed for our results but at a lower exposure time. Navarro, 2006 stated that pure CO_2 environments in laboratory settings can kill product-stored insects within 10 and 48 h, which could have been created by weevils and maize. Mortality can be attributed to its correlation with a hypoxia condition that causes body water loss (Navarro, 1978) thus leading to death. Also temperature within the barrels might have favored intensive oxygen intake by the weevils (Navarro, 2006; Navarro et al., 1994) thus leading to increased mortality. The fluctuations seen in Figs 7 and 8 were similarly observed by Hyde et al., 1973; Navarro et al., 1994, 1990; and Oxley and Wickenden, 1963 for both laboratory and field experiments, and it was attributed to a residual insect population that may remain behind after an extended period of time before a steady-state is attained. The steady-state conditions for our experiment were not only supported by the constant oxygen reading after some time but also by the zero number of weevils counted after unsealing of barrels, as opposed to Navarro et al., 1994 who reported that a residue population may be observed after the grain is re-exposed to oxygen.

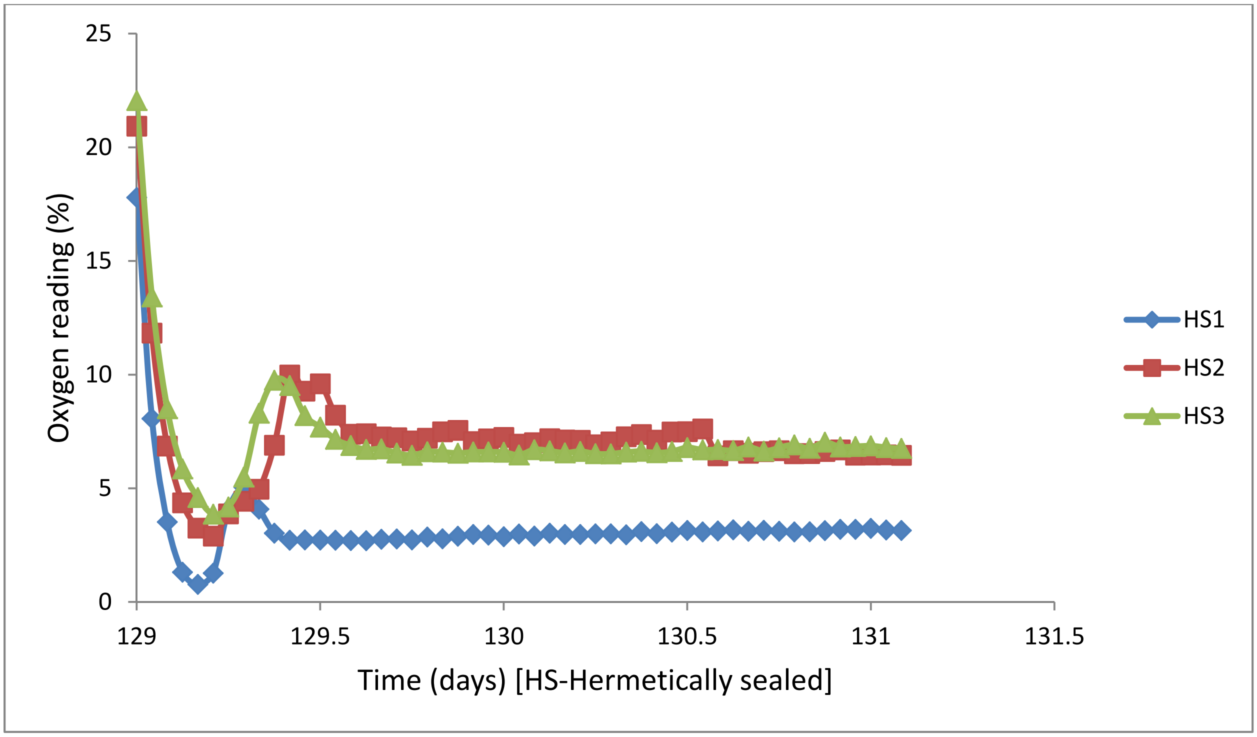

Figure 8: Oxygen content inside hermetically sealed barrels after T=129 days

Spoilage

At the end of the experiment there were spots of visible fungal growth on fine material and kernels near the barrel walls in both hermetic and non-hermetic treatments. Further investigation is needed to understand the specific cause of fungal growth as it was unexpected in view of the low moisture content (<14%).

Temperature

There was a range of 21.6 to 34.7^{0}C (70.9 to 94.5^{0}F) in temperature inside the barrels with 30.7^{0}C (87.2^{0}F) being the average. At T=120 days, temperatures inside NH1, NH2, NH3, HS2, and HS3 were not significantly different from each other while that of HS1 was significantly different from the rest of the barrels. After one day of sealing (T=122 days), the temperatures inside hermetic and non-hermetic barrels were not significantly different. At the end after barrels were resealed (T=150 days), the temperature inside hermetic and non-hermetic barrels were significantly different ($P<0.0001$). At T=190 days, the previously hermetically sealed barrels' temperature showed significant differences ($p<0.0001$) from those of non-hermetic barrels. The temperature values were attributed to respiratory and/or metabolic processes of maize and the weevils (Bern et al., 2013). Temperatures recorded inside the barrels were slightly higher than those recorded by Foster et al., 1955 (21.1 – 26.7^{0}C). This could have been because of having a controlled room temperature in comparison to their experiment which was exposed to winter, summer and spring weather. Because of the slightly higher temperature in the barrels moisture transfer and accumulation to the sides of barrels may have led deterioration of and/or moldy maize as observed when the barrels were emptied. Foster et al., 1955 observed a similar scenario. Navarro, 2006; and Navarro et al., 1994 reported that both mold and insects release heat which can lead to temperature gradients within the stored grain thus creating convection currents within the stored grain product, encouraging warm moist air movement from the heating section to cooler sections where moisture is dropped as air cools. The deterioration may have an effect on farmers' acceptance of the technology (Navarro et al., 1994).

Relative humidity

The relative humidity range was 59 to 83% inside the barrels with 70% being the average, and it showed an increasing trend with time. At T=120 days, relative humidities inside HS1, HS2 NH1, and NH2 were not significantly different from each other whereas those of HS3 and NH3 were significantly different from HS1, HS2 NH1, and NH2. After one day of sealing (T=122 days), relative humidities inside hermetic and non-hermetic barrels were not significantly different. At the end, after the barrels were resealed (T=150 days), relative humidity inside hermetic and non-hermetic barrels were significantly different (P<0.0001). At T=190 days, the previously hermetically sealed barrels' relative humidity showed significance difference (p<0.0001) from that of non-hermetic barrels.

Table 1: Summary of Tukey's mean comparison of U.S grade factors, and live weevils

Item	Treatment	T=0	T=40	T=80	T=120	T=122	T=150	T=190
Live weevils (#)	HS	25^{A}	9^{B}	44^{C}	84^{D}	17^{E}	0^{G}	0^{I}
	NH	25^{A}	8^{B}	70^{C}	114^{D}	114^{F}	141^{H}	214^{J}
BCFM (%)	HS	1.54^{K}	1.91^{L}	2.31^{M}	3.22^{N}	3.22^{O}	3.25^{P}	2.29^{Q}
	NH	1.65^{K}	1.91^{L}	2.28^{M}	2.82^{N}	2.82^{O}	3.25^{P}	2.38^{Q}
TW (lb/bu)	HS	57.4^{R}	57.1^{S}	56.7^{T}	56.2^{U}	56.1^{V}	55.5^{W}	55.2^{Y}
	NH	57.4^{R}	57.1^{S}	56.7^{T}	56.0^{U}	56.0^{V}	55.2^{X}	54.4^{Z}
MD (%)	HS	4.60^{A}	3.80^{B}	4.49^{C}	6.41^{D}	6.93^{E}	6.01^{F}	7.39^{G}
	NH	4.07^{A}	3.91^{B}	4.44^{C}	6.13^{D}	6.13^{E}	7.40^{F}	9.39^{H}
MC (%)	HS	13.0^{I}	13.3^{J}	13.2^{K}	12.8^{L}	12.8^{M}	13.3^{N}	12.8^{P}
	NH	13.2^{I}	13.4^{J}	13.3^{K}	12.8^{L}	12.8^{M}	13.1^{O}	12.8^{P}

Levels not followed by same letter at each item are significantly different at 0.05 level

CONCLUSIONS

- Hermetically sealed barrels resulted in 100% adult weevil mortality.
- Oxygen levels in hermetically sealed barrels declined from 21% to between 3 and 10 percent.
- HS vs. NH: BCFM was not significantly different at all times, MC was significantly different at T = 150 days, TW was significantly different (HS better) at T = 150 and 190 days, MD was significantly different (HS better) at T = 190 days.
- The Sukup Food Storage assembly can be a viable hermetic storage system for controlling maize weevils.
- Further investigation is necessary to understand the appearance of some molds in barrels.
- Farmers using this technology need not to fear maize quality loss and can sell their maize when prices are high.

IMPLICATIONS

- Hermetic storage in a 55-gallon barrel is a non-pesticide approach to controlling weevils in maize.
- No high level of expertise is needed to implement this technology.

Acknowledgements

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