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Evaluation of Hermetic Maize Storage in 208 Liter (55 Gal) Steel Barrels for Smallholder Farmers

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Abstract

Maize is an important crop for many smallholder farmers in the world. Maize weevils () cause a significant loss in quality and quantity during maize storage, especially in tropical regions. Hermetic storage of maize has been shown to be effective in controlling maize weevils in laboratory and field settings. The objective of this research was to test the effectiveness of steel barrels that could be used by smallholder farmers for hermetic storage. Six 208 L (55 gal) steel barrels were each loaded with 170 kg (375 lb) of maize at an average moisture of 13.4% w.b., with initial weevil population densities of 25 live weevils kg^{-1} (11 live weevils lb^{-1}) of maize. All six barrels were stored at 27°C (81°F) under non-hermetic conditions for 120 d, corresponding to approximately three weevil lifecycles. After 120 d, weevil population densities had increased to an average of 99 live weevils kg^{-1} (45 live weevils lb^{-1}) in all six barrels. Three of the six barrels were subsequently hermetically sealed. After an additional 30 days (150 days since experiment start), the weevil population densities were zero in every hermetically sealed barrel (100% mortality) and averaged 141 live weevils kg^{-1} (64Â live weevils lb^{-1}) in the non-hermetic barrels. All barrels where then exposed to non-hermetic conditions for an additional 40 days (approximately one weevil lifecycle). The barrels previously under hermetic conditions had zero live weevils, while the other barrels averaged 214 live weevils kg^{-1} (98 live weevils lb^{-1}), demonstrating that all stages of weevils (eggs, larvae, and pupae) were killed. Means of barrel oxygen content, test weight (TW), moisture content (MC), temperature, and humidity were significantly different between the hermetically sealed and control treatments. In contrast, broken corn and foreign material (BCFM) and mechanical damage (MD) were not significantly different. Hermetically sealed steel barrels may be an effective maize storage option for smallholder farmers.

Keywords

BCFM, Maize weevil, Mechanical damage, Moisture content, Mortality, Mycotoxins, Test weight

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EVALUATION OF HERMETIC MAIZE STORAGE IN 208 LITER (55 GAL) STEEL BARRELS FOR SMALLHOLDER FARMERS

D. Bbosa, T. J. Brumm, C. J. Bern, K. A. Rosentrater, D. R. Raman

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, especially in tropical regions. Hermetic storage of maize has been shown to be effective in controlling maize weevils in laboratory and field settings. The objective of this research was to test the effectiveness of steel barrels that could be used by smallholder farmers for hermetic storage. Six 208 L (55 gal) steel barrels were each loaded with 170 kg (375 lb) of maize at an average moisture of 13.4% w.b., with initial weevil population densities of 25 live weevils kg^{-1} (11 live weevils lb^{-1}) of maize. All six barrels were stored at 27°C (81°F) under non-hermetic conditions for 120 d, corresponding to approximately three weevil lifecycles. After 120 d, weevil population densities had increased to an average of 99 live weevils kg^{-1} (45 live weevils lb^{-1}) in all six barrels. Three of the six barrels were subsequently hermetically sealed. After an additional 30 days (150 days since experiment start), the weevil population densities were zero in every hermetically sealed barrel (100% mortality) and averaged 141 live weevils kg^{-1} (64 live weevils lb^{-1}) in the non-hermetic barrels. All barrels where then exposed to non-hermetic conditions for an additional 40 days (approximately one weevil lifecycle). The barrels previously under hermetic conditions had zero live weevils, while the other barrels averaged 214 live weevils kg^{-1} (98 live weevils lb^{-1}), demonstrating that all stages of weevils (eggs, larvae, and pupae) were killed. Means of barrel oxygen content, test weight (TW), moisture content (MC), temperature, and humidity were significantly different between the hermetically sealed and control treatments. In contrast, broken corn and foreign material (BCFM) and mechanical damage (MD) were not significantly different. Hermetically sealed steel barrels may be an effective maize storage option for smallholder farmers.*

Keywords. *BCFM, Maize weevil, Mechanical damage, Moisture content, Mortality, Mycotoxins, Test weight.*

Maize (*Zea mays*) is a major staple crop for smallholder farmers, with over 300 million consumers in Africa (Daily Guide, 2010). In 2014, maize was harvested on 183 million ha worldwide, resulting in 1.04 billion Mg of production (FAOSTAT, 2014). By 2025, maize will be the most highly produced crop globally (CIMMYT, 2011; Rosegrant et al., 2008).

The maize weevil (*Sitophilus zeamais*) can be extremely destructive to stored maize, with losses in excess of 50% reported (Boxall, 2001). The female weevil bores through the pericarp of undamaged kernels and deposits an egg into the intact inner portion of the kernel, which she then seals with a mucus-like substance. An adult female can lay about 300 to 400 eggs over a period of 4 to 5 weeks (Hill, 1987). The pupa consumes the inner portion of the kernel. After emergence, adult weevils damage grain by feeding on the endosperm of the kernel, as well as chewing 1.5 mm holes in the pericarp (Kranz et al., 1997). The average weevil lifecycle is 36 days at 27°C ±1°C and 69% ±3% relative humidity (Sharifi and Mills, 1971). Damage inflicted on the kernels provides potential openings for disease and fungal growth in the grain (CGC, 2013), creates dust, and lowers overall grain quality.

Hermetic storage of maize depletes oxygen and increases carbon dioxide inside a storage system due to respiration by maize and other living organisms (i.e., maize weevils) and container sealing, which prevents CO_2 venting and O_2 replenishment. When oxygen levels fall below about 5%, insect activity ceases and insects die (Gummert et al., 2004). Banks and Annis (1990), Fleurat (1990), and Navarro (1978) recommended oxygen levels below 3% for effective control. Atmospheres with depleted oxygen levels and elevated carbon dioxide levels can maintain grain quality for extended periods of time (Navarro et al., 2012).

Previous research studied the effects of maize temperature, time, maize moisture, and oxygen levels on maize weevil mortality during hermetic storage (Yakubu et al., 2011). Weevil-infested commercial hybrid maize samples in 476 mL (1 pint) jars were held under hermetic conditions at maize moisture levels of 6.3% and 16%, and at 10°C and 27°C. Hermetic conditions were effective in killing weevils, and the rate of mortality was affected by temperature and maize moisture content. Equations were developed and val-

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idated to predict the time to 100% adult weevil mortality as a function of maize temperature, moisture content, and initial oxygen volume.

Hermetic storage techniques have been implemented in many locations. Plastic bags (Baoua et al., 2013; Murdock and Baoua, 2014; Murdock et al., 2012) and steel drums (Murdock et al., 1997) have been extensively used to hermetically store cowpeas in West Africa. Both containers can be effective in preventing insect damage during storage. Plastic bagging uses one to three layers of polyethylene protected by an exterior woven bag. The Purdue Improved Cowpea Storage (PICS) bags (Purdue, 2016) and GrainPro bags (GrainPro, 2016) are in use today in developing countries. However, they are not effective against rodents, and some insects can bore through the bags, rendering them ineffective for hermetic storage. Steel drums are rodent-proof and have long life, but they also have a higher initial investment cost. Based on initial costs and projected useful life, Moussa et al., (2011) estimated annual storage costs at \$20 U.S. per Mg for plastic bags and \$16 U.S. per Mg for steel drums. Thus, steel drums may be a more effective storage strategy in the long term.

The Swiss Agency for Development and Cooperation introduced the Postcosecha galvanized steel silo in Central America in 1980. Hundreds of thousands are now in use in Central America, Africa, and elsewhere. The silos can be fabricated in sizes from 100 to 3000 kg and are built by local artisans using 26 gauge (0.7 mm) galvanized steel and lead-based solder (Tefera et al., 2011). The silos are effective in preventing storage losses due to rodents and birds. They can provide hermetic storage and consequent protection from insect pests only if they are properly sealed and filled to capacity to exclude as much air as possible.

Steel barrels are available in many developing countries, particularly sub-Saharan Africa. They may be potentially used for hermetic storage of maize by smallholder farmers. In light of the lower cost projected for steel drum storage methods, and the lack of prior work focused on hermetic storage of medium volumes of maize, the objective of this research was to evaluate the effectiveness of 208 L (55 gal) steel barrels for hermetic maize storage. The specific objectives were to determine weevil mortality in maize stored in sealed steel barrels, determine changes in maize quality during storage, and determine whether hermetically sealed maize becomes re-infested when unsealed.

Materials and Methods

Containers

Six 208 L (55 gal) open-head, unlined steel barrels (model 882-35, Sioux Chief Mfg. Co., Peculiar, Mo.) were used as storage containers. The barrels (fig. 1) could be covered either with: (1) screens (0.3 mm openings) to retain weevils yet allow for air passage (long ultra-sunblock solar screens, New York Wire, Mt. Wolf, Pa.) or (2) hermetically sealable lids from the experimental Sukup Food Storage system (Sukup Manufacturing Co., Sheffield, Iowa). Before use, the barrels were cleaned 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 commingled maize was used as the source of maize weevils, which were separated from the maize by passing the infested maize through a Carter Day Dockage tester (CEA, Minneapolis, Minn.) with 4.76 mm (12/64 in.) screen to retain the maize and a 0.99 mm (2.5/64 in.) screen to retain the weevils plus some fine material. Each barrel in the experiment required over 4000 weevils to be added. Rather than count all these weevils, the weevil additions were done on a mass basis, using the bulk density of three representative weevil samples (36.72 g per 1,000 weevils, 0.96 g standard deviation). For subsequent assaying for infestation, weevil numbers were determined by counting.

Experimental Design and Procedure

The experiment consisted of two treatments, hermetically sealed (HS) and non-hermetically sealed (NH), each with three replications. Six barrels were each loaded with 170 kg (375 lb) of weevil-free commercially commingled bulk maize at 13.4% moisture from the 2012 harvest in central Iowa. Each barrel was seeded with 25 live adult weevils kg^{-1} of maize (time $T = 0$ days) and covered with a screen to prevent weevil escape. The barrels were held in a 27°C ±2°C room from $T = 0$ days to $T = 190$ days. At $T = 120$ days, hermetically sealable lids were installed on three randomly selected barrels (designated HS1, HS2, and HS3). The remaining barrels (NH) were again covered with a screen. The first 120 days, approximately three lifecycles, allowed the weevils to reproduce and become established. At $T = 121$ days, the three hermetically sealed bar-

Figure 1. Barrels used for (left) non-hermetic and (right) hermetic storage.

Table 1. Procedures for maize storage in the barrels (three hermetically sealed, and three non-hermetically sealed).

Time (d)	Barrel Treatment[a]	Procedure
0	All	Loaded with 170 kg of maize and 25 live weevils per kg of maize, unsealed
120	All	Sampled
	HS	Hermetically sealed
121	HS	Unsealed to diagnose an apparent sensor problem
122	HS, NH	Sampled
129	HS	Hermetically sealed
150	HS	Unsealed, sampled, and covered with screen
	NH	Sampled
190	HS, NH	Sampled

[a] HS = hermetically sealed barrels, NH = non-hermetically sealed barrels, and All = both HS and NH barrels.

rels were opened due to suspected malfunctioning of the oxygen sensors. After observation and sampling, the three barrels were each covered with a screen and then re-sealed at T = 129 days. The calculated time to 100% mortality for the hermetically sealed barrels at a weevil count of 17 weevils per kg (the amount present at T = 121 days) was 20 days (Yakubu et al., 2011). Based on this calculation, at T = 150 days, all barrels were opened and sampled. From T = 150 to T = 190 days (approximately one lifecycle), all barrels were left covered with screens to prevent escape of weevils. The purpose of this last period was to allow any surviving weevils in other life stages (eggs, larvae, and pupae) to emerge so they could be identified. Table 1 summarizes the procedure for the two treatments.

Measurements

Representative samples of the maize were drawn at different times using a brass sampling probe (Seedburo, Des Plaines, Ill.) inserted diagonally three times into each barrel. Weevil mortality in the samples was determined (Gullan and Cranston, 2010; Yakubu et al., 2011). Samples were analyzed for broken corn and foreign material (BCFM) (USDA, 2013), moisture content (ASABE, 2006), test weight (TW) (USDA, 1996), and mechanical damage (MD) (Steele et al., 1969). Mechanical damage is the weight percentage of any kernels with a missing portion, a visible crack, or a rupture in the seed coat (as defined by Steel et al., 1969) as made by visual examination of individual kernels on a light table, and includes insect damage. The oxygen level inside the hermetically sealed barrels was measured using oxygen sensors (model 65, AMI, Huntington Beach, Cal.) mounted in the center of the sealable lids and connected to a computer via a PMD 1408FS DAC system. The oxygen sensors were calibrated by the manufacturer immediately before use and have a sensitivity of 0.13 percentage points of oxygen. Aflatoxin analysis was performed on grab samples from all six barrels at the end of the experiment using a ROSA-M reader (Charm Science, Inc., Lawrence, Mass.), which detects the sum of aflatoxins B1, B2, G1, and G2. Temperature and relative humidity inside the barrels were measured using temperature and humidity loggers (Haxo-8, Contoocook, N.H.), with one placed in the middle of the grain mass in each barrel.

Data Analysis

One-way ANOVA and Tukey's means comparison were performed to determine statistical significance in treatments at α = 0.05 using JMP Pro 10 (SAS Institute, Inc., Cary, N.C.).

Results and Discussion

Weevil Mortality

The initial population density was 25 weevils kg^{-1} of maize (table 2). From time T = 0 to T= 120 days, the weevils were left to go through approximately three lifecycles to increase population density, resulting in an average of 99 weevils kg^{-1} across all barrels when three randomly selected barrels were hermetically sealed.

The three HS barrels were unsealed at 121 days due to a suspected malfunction of the oxygen sensors. Upon unseal-

Table 2. Mean number of live weevils and maize quality factors for hermetically sealed (HS) and non-hermetically sealed (NH) barrels over time.[a]

	Barrels[b]	T = 0 days	T = 40 days	T = 80 days	T = 120 days	T = 122 days	T = 150 days	T = 190 days
Number of live weevils (kg^{-1})								
	HS	25 ±0 Abc	9 ±2 Acd	44 ±12 Ab	84 ±13 Aa	17 ±11 Acd	0 ±0 Ad	0 ±0 Ad
	NH	25 ±0 Ad	8 ±5 Ad	70 ±17 Acd	114 ±30 Abc	114 ±30 Bbc	141 ±29 Bb	214 ±29 Ba
Temperature (°C)								
	HS	N/A	30.6 ±6.0 Uc	31.3 ±1.5 Ua	30.9 ±1.9 Ub	30.7 ±1.4 Uabc	28.1 ±1.4 Ud	30.5 ±2.3 Uc
	NH	N/A	30.6 ±6.3 Uc	31.6 ±1.6 Ta	31.2 ±1.5 Tb	30.5 ±1.2 Ubc	31.3 ±1.3 Tab	31.6 ±1.7 Ta
Relative humidity (%)								
	HS	N/A	65.2 ±1.3 Mf	66.9 ±1.0 Me	69.9 ±0.7 Md	71.5 ±0.4 Mb	70.4 ±0.7 Mc	74.5 ±1.1 Ma
	NH	N/A	64.8 ±1.2 Nf	66.6 ±1.0 Ne	69.4 ±1.4 Nd	70.9 ±1.8 Mc	72.6 ±2.0 Nb	74.7 ±2.7 Ma
Moisture content (%)								
	HS	13.0 ±0.6 Dab	13.3 ±0.0 Da	13.2 ±0.1 Dab	12.8 ±0.1 Dab	12.8 ±0.1 Dab	13.3 ±0.1 Dab	12.8 ±0.2 Db
	NH	13.2 ±0.1 Dab	13.4 ±0.2 Da	13.3 ±0.1 Dab	12.8 ±0.1 Dc	12.8 ±0.1 Dc	13.1 ±0.1 Ebc	12.6 ±0.1 Dc
Mechanical damage (%)								
	HS	4.6 ±1.8 Xbc	3.8 ±0.5 Xc	4.5 ±0.4 Xbc	6.4 ±1.0 Xab	6.9 ±0.9 Xab	6.0 ±0.4 Xabc	7.4 ±0.4 Xa
	NH	4.1 ±0.9 Xd	3.9 ±0.3 Xd	4.4 ±0.5 Xcd	6.1 ±0.6 Xbc	6.1 ±0.6 Xbc	7.4 ±0.9 Xb	9.4 ±1.1 Za
Broken corn and foreign material (%)								
	HS	1.5 ±0.1 Kc	1.9 ±0.1 Kbc	2.3 ±0.1 Kabc	3.2 ±0.5 Kab	3.2 ±0.5 Ka	3.3 ±0.5 Ka	2.3 ±0.5 Kabc
	NH	1.7 ±0.5 Kc	1.9 ±0.1 Kbc	2.3 ±0.3 Kbc	2.8 ±0.3 Kab	2.8 ±0.3 Kab	3.3 ±0.4 Ka	2.3 ±0.3 Kbc
Test weight (lb bu^{-1})								
	HS	57.4 ±0.2 Ra	57.1 ±0.1 Rab	56.7 ±0.2 Rbc	56.2 ±0.1 Rcd	56.1 ±0.2 Rde	55.5 ±0.1 Re	55.2 ±0.2 Rf
	NH	57.4 ±0.2 Ra	57.1 ±0.1 Rab	56.7 ±0.2 Rbc	56.0 ±0.1 Rc	56.0 ±0.1 Rc	55.2 ±0.1 Sd	54.4 ±0.2 Sd

[a] Means followed by different uppercase letters within each time (column) and means followed by different lowercase letters within each barrel group (row) for each factor are significantly different at the 0.05 level.

[b] HS barrels were hermetically sealed at T = 120, opened at T = 122, resealed at T = 129, opened at T = 150, and resealed at T = 151.

ing, apparently dead weevils were seen to have accumulated mostly on top of the maize, below the oxygen sensors, and on the sides near the tops. After 24 h of exposure to ambient air with screens on top (T = 122 days), all barrels were sampled. Live weevils dropped from 84 to 17 weevils kg^{-1} on average in the HS barrels. The calculated expected time to 100% mortality for 99 weevils kg^{-1} was 8 days (Yakubu et al., 2011), so this degree of mortality was unexpected. It could be, but unlikely, that a significant number of weevils were killed in the one day of hermetic sealing. More likely is that the while the weevils seemed to be dead by visual observation, some were just dormant and became active again after exposure to oxygen. This could have been a narcotic effect of carbon dioxide, leading to immobilization of weevils (Aliniazee, 1971; Edwards and Rollas, 1973; Navarro, 2006).

The three HS barrels were left unsealed for seven days (from T = 122 to T = 129) but with screens on top to prevent escape of live weevils. At T = 129 days, the HS barrels were sealed again. The calculated expected time to 100% mortality for 17 weevils kg^{-1} was 20 days (Yakubu et al., 2011). The HS barrels were exposed to ambient air for 24 h at T = 150 days. After 24 h, all barrels were sampled, and the population density was zero live weevils kg^{-1} in each of the HS barrels. From T = 150 to T = 190 days, all six barrels were left with screens on top to prevent escape of weevils. The purpose of this period was to determine if the hermetic storage influenced other life stages of maize weevils, that is, eggs, larvae, and pupae.

At T = 120 days (before hermetically sealing), there was no significant difference in the number of live weevils between the HS and NH barrels ($F_{1,4}$ = 2.55, p = 0.1857). At T = 122 days ($F_{1,4}$ = 28.28, p = 0.0060), at T = 150 days ($F_{1,4}$ = 71.14, p = 0.0011), and at T = 190 days ($F_{1,4}$ = 162.78, p = 0.0002), the effect due to treatment was significant. In each case, the number of live weevils in the NH treatment was significantly greater. The weevil population decline from T = 0 to T = 40 days was attributed to the weevils not yet being adapted to their environment, and some were probably ending their lifecycle. The population increase in all the barrels after T = 40 days was because of the favorable maize moisture content and temperature (Sone, 2000). The complete mortality in the HS treatment was because of oxygen depletion and likely 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).

Navarro et al. (1994) reported that a residual population may be observed after hermetically stored grain is re-exposed to oxygen. That was not the case here. At the end of the experiment (T = 190 days), there were zero live weevils in the HS treatment due to the hermetic storage effect on other life stages of maize weevils (egg, larvae, and pupae), and the large population of live weevils in the NH treatment (214 weevils kg^{-1} on average) was due to favorable temperature, maize moisture content, and availability of kernels.

Temperature

There was a temperature range of 28.1°C to 31.3°C (82.6°F to 88.3°F) in the hermetically sealed barrels and 30.5°C to 31.6°C (86.9°F to 88.9°F) in the non-hermetic barrels, with 30.7°C (87.2°F) being the overall average. At T = 80, 120, 150, and 190 days, temperatures in the non-hermetic barrels were significantly higher than in the hermetic barrels, probably because of weevil respiration. All recorded temperatures were higher than the 27°C room temperature. The higher temperature values were attributed to respiratory and/or metabolic processes of maize and the weevils (Bern et al., 2013).

Relative Humidity

The measured relative humidity range was 59% to 83% inside all barrels, with an overall mean of 70%, and increased over time. There were statistically significant differences between barrel treatments in relative humidity at T = 120 days ($F_{1,1437}$ = 53.46, p < 0.0001) and T = 150 days ($F_{1,754}$ = 386.79, p < 0.0001). However, these differences between barrel treatments (0.5 percentage points and 2.2 percentage points for T = 120 and T = 150, respectively) were of no practical significance.

Maize Moisture Content

Average maize moisture ranged from 13.4% to 12.5% for all barrels during the 190 days of the experiment. In general, the moisture contents within barrel treatment (HS and NH) were not significantly different. Similarly, there was generally no significant difference in moisture content between barrel treatments, except for T = 150 days when the HS barrels were slightly higher in moisture content ($F_{1,4}$ = 7.84, p = 0.0488). This difference (0.2 percentage points) was not practically significant. At T = 190 days, moisture content was not significantly different between barrels ($F_{1,4}$ = 1.35, p = 0.3092).

Maize Quality

Mechanical damage (MD) is the percentage by weight of kernels with a missing portion or any visible crack or rupture of the seed coat (Steele et al., 1969). There was an increasing trend from 4.34% to 8.43% on average in all treatments. MD was not significantly different between all barrels during the weevil population increase (T = 0 to T = 120 days). There were no significant differences between HS and NH treatments after one day of sealing, i.e., T = 122 days ($F_{1,4}$ = 1.58, p = 0.2769) and after complete resealing, i.e., T = 150 days ($F_{1,4}$ = 6.44, p = 0.0642). However, MD was significantly lower in the HS treatment than in the NH treatment at T = 190 days ($F_{1,4}$ = 9.85, p = 0.0349). Increased mechanical damage over time was attributed to the increasing number of weevils in the barrels. The significant difference in mechanical damage between treatments at the end of the experiment was due to the lack of live weevils in the HS treatment. This result is in line with the results observed by Foster et al. (1955).

There was an increase in the broken corn and foreign material (BCFM) in all barrels from 1.6% to 3.3% on average from T = 0 to T = 150 days. BCFM values were not significantly different between HS and NH treatments at any time (T = 122: $F_{1,4}$ = 1.52, p = 0.2851; T = 150: $F_{1,4}$ = 0.34, p = 0.5888; and T = 190: $F_{1,4}$ = 0.065, p = 0.8112). However, at T = 190 days, the BFCM in the NH barrels showed an unexpected significant decrease. Although care was taken in randomly sampling each barrel, it is possible that the NH samples taken at 190 days were not representative (sampling error).

There was a decline in test weight (TW) from 57.4 to 54.8 lb bu^{-1} (739 to 705 kg m^{-3}) on average during the experiment. During the first 120 days, TW was not significantly different between treatments. TW was significantly higher for the HS treatment at T = 150 days ($F_{1,4}$ = 14.29, p = 0.0194) and at T = 190 days ($F_{1,4}$ = 32, p = 0.0048). TW generally declines with increasing moisture content (Nelson, 1980); however, there were no significant changes in moisture content from T = 120 to T = 190 days. Changes in TW are attributed to weevil consumption of the maize kernels, or in the case of HS barrels at T = 190 days, potential sampling error, as discussed earlier.

Mold and Mycotoxins

At the end of the experiment, there were regions of visible fungal growth (storage mold) on fine material and kernels clinging to the barrel walls in all barrels, amounting to less than 1% of the grain mass. The moisture content of the grain did not significantly change over the course of the experiment, but condensation could have occurred. For example, at T = 190 days, the average conditions in the barrels (31°C and 74.6% RH) resulted in a dew point of 26°C, which was close to the room temperature of 27°C. It could be that localized conditions within the barrels had a dew point at or above the room temperature, thus resulting in condensation that promoted mold growth. Additionally, Navarro (2006) stated that metal silos have a disadvantage of moisture migration and condensation in hot climates, where temperature conditions are similar to those in our experiment.

Grab samples of moldy maize from each barrel were analyzed for aflatoxin. Samples from the three HS barrels had total aflatoxin (B1, B2, G1, and G2) concentrations of 0, 3, and 30 ppb, respectively. Samples from the three NH barrels had total aflatoxin concentrations of 1, 2, and 2 ppb, respectively. Note that the kernels analyzed were not representative of all the moldy maize nor of all the maize in the barrels. However, occurrence of aflatoxin at any level is of concern and requires further study. Storage of maize at moisture contents lower than in this study (12.6% to 13.4%) should reduce the potential for condensation, mold, and mycotoxins.

Oxygen Levels under Hermetic Conditions

There was a general decline in oxygen level from 23% to 3% on average in the three HS barrels from T = 120 to T = 120.2 days. The oxygen levels then increased to 6.7% from T = 120.2 to T = 120.4 days, and finally there was a decline to a constant value of 5.5% on average up to T = 120.8 days (fig. 2). Oxygen levels inside the HS barrels were significantly lower than the atmospheric oxygen level ($F_{1,59}$ = 9.84, p = 0.0027) during this entire period. The intermediate increase in oxygen levels led to the suspicion that the sensors were malfunctioning. However, a subsequent validation of the sensors showed no malfunction.

After resealing the barrels at T = 129 days, the oxygen levels followed almost the same trend (fig. 3) as previously seen after T = 120 days (fig. 2), with a decline of below 5%

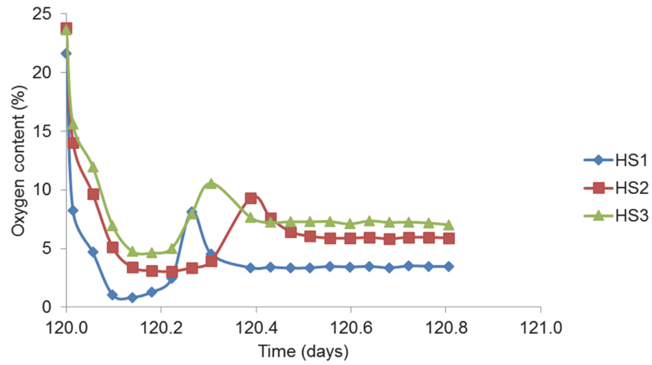

Figure 2. Oxygen content inside hermetically (HS) sealed barrels starting at T = 120 days.

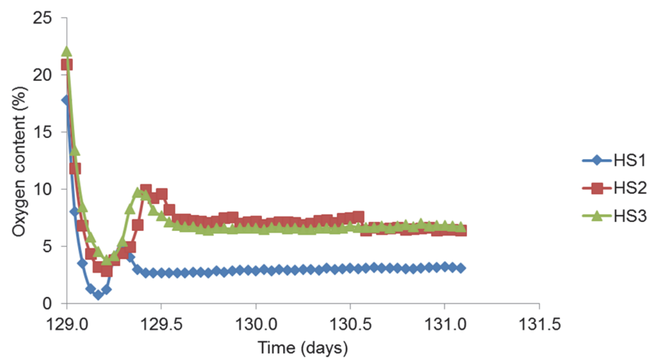

Figure 3. Oxygen content inside hermetically sealed (HS) barrels starting at T = 129 days.

on average at T = 129.2 days, followed by a rise of between 5 and 10 percentage points, and then a decline to a constant value in each barrel. Oxygen levels remained nearly constant in all three HS barrels from T = 130.4 days to the end of the experiment (T = 149 days). Oxygen levels inside the HS barrels were significantly lower than the atmospheric oxygen level ($F_{1,152}$ = 27.71, p < 0.0001).

The decline in oxygen with time was expected; however, the slight increase between 129.25 and 129.5 days and the rapid decline in oxygen ahead of the calculated complete mortality date were unexpected. The trend was similar to that observed by Villers et al. (2010) while studying hermetic storage of cocoa beans. Fluctuations in oxygen content similar to those seen in figures 2 and 3 were also observed by Hyde et al. (1973), Navarro et al. (1994, 1990), and Oxley and Wickenden (1963) for both laboratory and field experiments.

Complete weevil mortality was achieved with oxygen levels above the 3% level recommended for complete mortality by Banks and Annis (1990), Fleurat (1990), Navarro (1978), and Navarro et al. (2012) for effective control. Bailey (1955, 1956, 1957, 1965) suppressed storage insects at about 5% oxygen with longer exposure time, which is nearly the same concentration observed for our results but at a shorter exposure time. There could also have been a synergistic effect of reduced oxygen and increasing carbon dioxide (Aliniazee, 1971); however, carbon dioxide levels were not measured, so this could not be verified.

CONCLUSIONS

Storage of maize in 208 L (55 gal) open-head, unlined steel barrels that were hermetically sealed resulted in 100% adult weevil mortality, although the 3% level of oxygen recommended for weevil mortality was not maintained in the barrels. Maize quality decreased due to the presence of weevils, but maize quality was maintained when the maize was hermetically stored. Hermetic storage also killed weevil eggs, larvae, and pupae. Storage of maize in such containers can be an effective approach to controlling weevils in maize.

Moldy maize was observed on the walls of both sealed and unsealed barrels. Hermetic storage of maize at moisture contents lower than those in this study (12.6% to 13.4%) should reduce the potential for mold. However, the appearance of mold necessitates further research. Future research should also include evaluating hermetic storage with smallholder farmers in developing countries.

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