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Performance of Small-Scale Hermetic Storage Systems Under Periodic Access

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Abstract: This study characterizes the grain management performance of a novel integrated grain drying and storage system (iGDSS) adapted from 208 L drums to combat postharvest loss in developing countries through providing in situ mechanized drying and hermetic storage. The six-month storage trials of 14% moisture content maize compared different access mechanisms and two levels of pest pressure: 0 and 10 maize weevils/kg grain. This experiment allowed comparisons of differential oxygen consumption rates in small-scale hermetic systems with and without storage pests, which has not been widely reported in the literature. The iGDSS system was found to maintain grain quality parameters in dry grains with and without storage pests. After six months of storage, the results demonstrated no statistically significant difference in the moisture content, test weight, germination, proportion of broken and damaged kernels, and presence of colony-forming units between inoculated and non-inoculated systems. The iGDSS was also found to maintain oxygen intrusion rates of 0.10–0.13% O_2/day, below recommended thresholds of 0.15% required to maintain benefits of modified atmosphere storage. These results indicate that the iGDSS can provide safe and reliable grain storage to smallholder farmers in developing countries, and that the drying functions of iGDSS can promote outcomes in hermetic storage.

Keywords: postharvest loss; appropriate technology; grain quality

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1. Introduction

Postharvest loss (PHL) rates of staple grain crops threaten food security, especially as many developing countries experience high PHL rates and high population growth rates [1,2]. Investigations have found that most PHL occurs during storage, and this has been a focus area for technological intervention addressing primarily pest pressures and high grain moisture [3,4]. Storage pests lead to direct loss of grains and contribute to greater degradation, as insects can serve as vectors or dispersers of mold within grain and increase the surface area accessible for fungal colonization [5–7].

Hermetic storage is widely studied for mitigating PHL in developing countries as it provides a chemical-free alternative to insecticides, which are associated with negative environmental and human health impacts [4,8]. Hermetic storage creates an airtight barrier around the grain, allowing natural respiration of grains, insect pests, and microflora to reduce oxygen in the environment and reduce the activity and populations of storage pests. Large-scale flexible hermetic storage structures of up to 10,000-ton capacity have been used for storage and transport of commodities including cocoa, coffee, pulses, and grains, using either organic oxygen depletion or injecting nitrogen or carbon dioxide to accelerate oxygen depletion [9]. In the context of small farmers in developing countries, chemical insecticides may also be expensive, unavailable, adulterated, or applied inappropriately, and appropriately sized hermetic storage systems have been developed including PICS bags and GrainPro bags, with capacities of 50–100 kg, and specially constructed steel silos with capacities of 90–3000 kg supported by the Postcoescha program of the Swiss Agency for Development and Cooperation [10–12].

Respiration rates and time to critical low-oxygen levels are highly dependent on temperature, grain moisture, and the density of storage pests. Most studies looking at the effects of temperature, moisture, and pest density on oxygen depletion rates are carried out in benchtop scale, with high densities of insects, ranging from 36 to 486 adults/kg grain [13–15]. These types of densities can be achieved more easily in experiments carried out in 1 L storage systems, with less than 0.5 kg of grain, but are much more resource-intensive to carry out in full-scale systems with storage capacities of 50–150 kg grain.

Among full-scale studies that have been carried out, there are few identified which compare hermetic performance under known pest densities, because it is difficult to rear high volumes of pests or to quantify natural infestation levels. To overcome the unknown levels of natural infestation, one study sought to quantify the impacts of different initial pest densities by comparing naturally infested grain to grain that was additionally inoculated with 1 adult/kg [16]. This was the only study identified which included a comparison between different pest densities, but they only reported on differential numbers of adult grain borers and holes made by grain borers in PICS bags, otherwise combining natural and artificial infestation treatments in their analysis of moisture content and grain losses [16]. Thus, there was little found in the literature that compared the impact of differing initial densities of storage insect pests in hermetic storage on grain quality or modified atmosphere composition. In practice, pest densities can greatly differ year to year, and hermetic technologies should be able to perform well for grain preservation regardless of pest densities.

There has also been a lack of investigation in the literature on the impacts of oxygen intrusion when sampling from hermetic storage systems. Guidelines for the use of hermetic storage technologies include recommendations for removing excess oxygen when initially sealing the system, with excess headspace air minimized in PICS with the tying of inner plastic bag layers, and recommendations to burn a candle in the headspace of Postcosecha steel silos to reduce oxygen levels, although the impact on initial oxygen levels of these strategies has not been quantified [12,17]. In many long-term storage trials, researchers regularly sampled from nominally hermetic storage systems at monthly or bimonthly intervals, without reporting on oxygen levels or reporting only immediately before sampling [12,18,19]. In one lab study that evaluated oxygen levels immediately before and after 30 min of opening hermetic storage bags in a high-humidity environment, they found that repeatedly breaking the seal and accessing hermetic systems contributed to greater aflatoxin development [20]. However, though systems were opened weekly in the study, grain was only removed at 8 and 24 weeks, differing from a pattern of regularly removing grain that would be practiced by end-users [20]. Multilayer hermetic storage systems are also susceptible to puncture by rodents or storage pests like larger grain borers *Prostephanus truncatus*, and time can elapse before researchers or end-users notice the barrier is punctured [18,21]. In this study, rigid containers will be employed for hermetic storage, and careful monitoring of oxygen levels throughout the study will give insight into oxygen re-introduction with regular sampling with two different access mechanisms.

Another parameter that may impact storage outcomes is the management of grain during drying. Traditional, widely practiced methods of field-drying or sun-drying (laying grains on the ground or tarps) can expose grains to mycotoxigenic fungi, including soil-borne *Aspergillus flavus* [22,23]. Because mold can still develop in hermetically stored grain, and insect mortality under hermetic management decreases with increasing moisture content, most studies conclude that maize should be adequately dried to below 14% before hermetic storage [8,20,24–26]. This may not always be achieved in traditional drying practices, and many farmers rely on qualitative methods to assess moisture [27].

Thus, to address issues of high moisture and pest pressure that threaten safe storage, a novel integrated grain drying and storage system (iGDSS) was developed. The system combines functions of mechanized forced air-drying and hermetic storage in a rigid container. Considering the context and potential use cases of this system in developing countries, the system was designed around a widely available material, metal 208 L (55 gallon) drums,

and was designed with an access mechanism to reduce oxygen intrusion during sampling. The overall goal of this paper was to evaluate the storage performance of the iGDSS through experiments simulating potential use cases by smallholder farmers in developing countries. Thus, the objectives of this paper are to (1) evaluate grain quality differences in a 6-month hermetically sealed system compared to systems accessed biweekly after differential initial hermetic periods; (2) evaluate changes in grain quality and modified atmosphere conditions in hermetic systems stored with and without inoculated storage pests; and (3) evaluate oxygen re-entry and pest activity during periodic opening and grain removal in hermetic storage systems with and without inoculated storage pests.

2. Materials and Methods

A cross-factor design was utilized to examine the effects of the access mechanism, initial hermetic period (IHP), and pest inoculation across three replicates of six storage and access treatments of dried dent corn. An additional set of three treatments was intended to capture storage performance of iGDSS when used with undried grains, so grain was stored at harvest moisture content, averaging 28.09%. These experimental units had immediate and extreme decay and were not suitable for handling. Thus, results from the undried grains are not presented here.

The two access mechanisms examined included an airtight two-piece twist-off lid (Model: LD5GRLWH006, Leaktite Corp., Leominster, MA, USA) fitted to an 18.9 L (5 gallon) bucket, and a rubber-ringed hole plug fit into a 7.62 cm (3″) hole in the side of a 208 L (55 gallon) drum (Model: 33402D, Oatey, Cleveland, OH, USA). The different access mechanisms were utilized on treatments with different initial hermetic storage periods, with the 3- and 6-month IHP treatments being smaller in volume due to space and resource limitations and the lower required volume for analysis, and the 7-week IHP utilizing the iGDSS system adapted from 208 L drums. The standard 208 L drums were adapted into an integrated grain drying and storage system (iGDSS) (Figure 1), with an airtight lid, on-floor duct system, two 7.62 cm holes on the bottom side of the drum fitted with hole plugs, and a headspace analysis port with a 0.32 cm (1/8″) hole filled in with silicone. The vertical distance between the access point of the barrel and the port for headspace analysis was approximately 78 cm (31″).

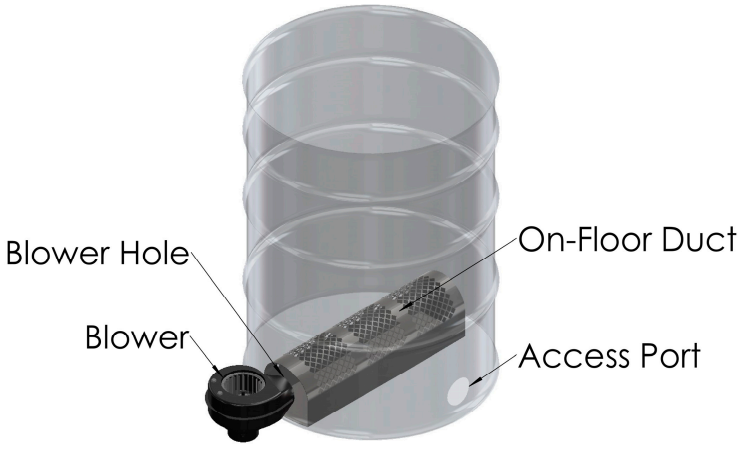


Figure 1. Components of iGDSS created from repurposed 208 L drums.

All maize was dent corn grown in Wooster, Ohio, at the Ohio State Experiment Station. All dried maize was dried in-bin using an on-floor duct to a final average moisture content of 13.7%. All treatments stored in iGDSS were dried in situ, and grain used in the smaller-scale 3-month and 6-month treatments was also dried using the in-bin system in a 208 L drum. Three blowers (Model: 1TDN6, W.W. Grainger, Lake Forest, IL, USA) were used to dry the drums concurrently, so some grains had a longer residence time of up to 4 days in the greenhouse at an average temperature of 26 °C at a higher moisture content of 28.09%

before being dried, which could impact initial quality parameters. The distribution of first- and last-dried drums was randomized in the storage trial.

Insects used in inoculation were maize weevils, *Sitophilus zeamais*, initially reared on whole oats and conditioned in the lab on dent corn for at least two generations (60 days) to ensure their habituation to corn. The inoculation rate of 10 adults/kg is on the high end of the range of pest density used in full-scale studies, which ranged from 1 to 25 adults/kg [18,28]. All treatments were inoculated at the same time 24 h after drying had been completed, and immediately before systems were hermetically sealed.

Storage trials began in December 2022 and ended in June 2023. The experiment was designed to simulate expected use in a subtropical climate, so storage containers were kept in a greenhouse chamber in Columbus, Ohio, which was temperature regulated to a target range of 22.8–25 °C and contained growing plant materials on grow tables, which were regularly irrigated and increased ambient humidity levels. This aligns with expected on-farm storage conditions where storage containers may be sheltered from precipitation but not from temperature and humidity swings. The experimental storage containers were arranged against one wall of the 7.6 × 15.2 m greenhouse chamber. Throughout storage, the air temperature and relative humidity in the ambient environment were monitored and logged every thirty minutes (Model: MX1101, Onset Corporation, Cape Cod, MA, USA), the O_2 and CO_2 levels in the storage containers were monitored twice-weekly, and grain was sampled initially and then biweekly following the IHP. Biweekly sampling was chosen to simulate frequent access by subsistence households. Moisture content was evaluated at each sampling, and additional grain quality parameters of germination, test weight, and presence of colony-forming units (CFUs) were assessed initially and at 7 weeks, 3 months, and 6 months. The proportion of broken and damaged kernels was assessed initially and at 6 months. The majority of data loggers recording intergranular temperature and relative humidity failed during the course of the experiment, likely due to the presence of fines in the grain, and thus the temperature and relative humidity data are not presented here.

Oxygen and carbon dioxide in the headspace of the barrels and buckets were measured with a handheld headspace analyzer outfitted with a needle tip (Model: FD-600-CO2-O2, Forensic Detectors, Rolling Hills Estate, CA, USA). The sensor has a resolution of 0.01% and specified error $\leq \pm 3\%$ for both oxygen and carbon dioxide. The headspace conditions were monitored twice weekly between samplings, and on sampling days were measured immediately before sampling and 30 min after the containers had been sealed again. The headspace analyzer also experienced a period of sensor failure, and the readings immediately preceding the sensor failure were discarded because of inaccuracies. The sensor was sent off for repair and calibration, and an alternate headspace analyzer by the same manufacturer was used to collect CO_2 readings for six sampling periods. After the sensor had been repaired and calibrated, the data collected from that point to the end of the storage trial were used to create a regression equation to calculate the missing values for oxygen readings based on the measured carbon dioxide levels. Linear regression equations were generated with a best-fit linear equation for the dried grains and gave an R^2 of 0.9488. The regression equation was used to calculate the oxygen levels for the missing samples.

To better represent use under intended conditions by smallholder farmers, grain was sampled every 2 weeks after the IHP, gathered in a 2 L paper bag, and transported to the lab for analysis. Test weight was measured by using a digital handheld density tester which was precise to 2 g (Model: 26HS, Seedburo Equipment Co., Des Plaines, IL, USA). The moisture content of the corn was determined using an oven-drying method with three replicate samples (30 g) prepared in brown paper bags and kept in a 100 °C oven for 72 h [29]. Germination was determined for three replicates of 50 kernels per sample by spreading kernels in a single layer on a cloth-like paper rag (Wypall, Kimberly-Clark Professional, Roswell, GA, USA) that had been moistened in DI water. The Wypall was then doubled over so the seeds were in contact with moistened paper, and then rolled and placed into a sealed plastic bag and incubated for 7 days at 30 °C [20,30]. After incubating, the bags were opened and the number of grains which had germinated was recorded. The

number of colony-forming units (CFUs) on the grains' surface was determined using a surfactant rinse and incubation on a fungi-promoting medium [31]. For each sample, 25 g of corn was rinsed in 50 mL of 0.05% Triton X-100 solution and shaken for two minutes. Then, the solution was serially diluted on malt salt agar and incubated for 7 days at 25 °C. After 7 days of incubation, the number of colonies was recorded. Broken and damaged kernels were assessed visually, considering discoloration, cracks, broken kernels, and evidence of holes from insect bites. Colony counts were not assessed if they were below 25 or above 250, and dilutions of 10^{-2} were assessed, which yielded over 70% countable plates in all instances [32].

A single-factor ANOVA was performed for each grain quality parameter and each sampling period to compare treatments. Post hoc analysis with Student's *t* test at a significance level of 0.05 was used to identify significant differences between treatments at each sampling period and within treatments over time.

3. Results

3.1. Temperature and Relative Humidity

The monthly average ambient temperature remained within the range of 24–28 °C compared to the target greenhouse setpoint of 22.8–25 °C. Temperatures were more stable for the first three months of the storage trial and became higher starting in June and July, and the standard deviations across all treatments increased over time (Figure 2). Relative humidity varied widely in the ambient environment in the greenhouse, as the greenhouse compartment was also used for plant production throughout the storage period, with irrigation typically taking place multiple times a week; thus, relative humidity is not displayed in Figure 2. The standard deviation of ambient relative humidity averaged 16.17 across the monthly periods.

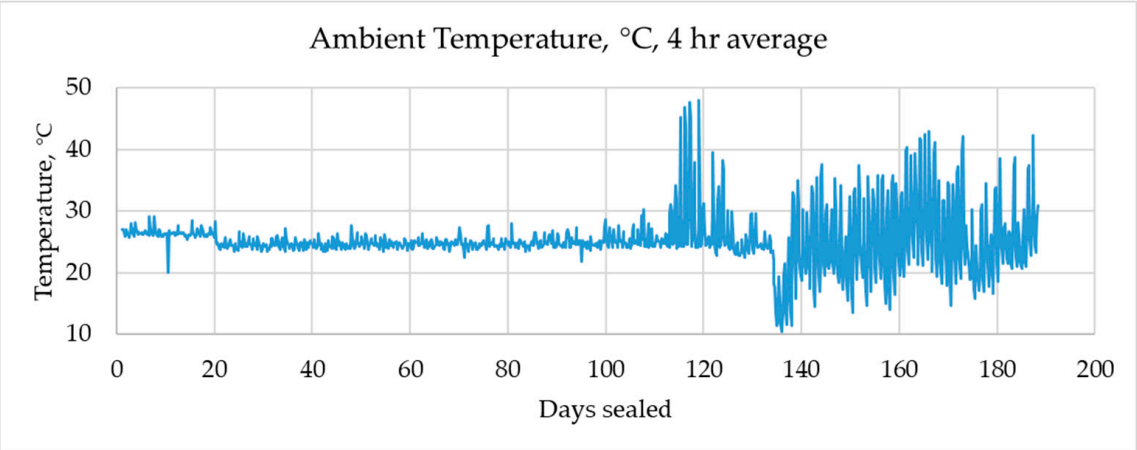


Figure 2. Ambient temperatures in greenhouse chamber across storage trial. Day 0 corresponds to 13 December 2023.

3.2. Grain Quality Parameters

3.2.1. Moisture Content

Maize had an initial average moisture content of 13.7% before storage, and each replicate showed a statistically significant increase to an average of 14.9% after six months of storage. Although the trend was an increase in moisture, there was an intermediate decrease in moisture level reflected in the 3-month sampling (Table 1), though this was only a significantly different decrease for one treatment, the non-inoculated system with a 3-month IHP. There was a statistically significant ($p < 0.05$) increase in moisture content from the 3-month to the 6-month sampling period across all systems that underwent periodic access, and in the 6-month hermetic treatments, an increase from initial to 6 months. Within each initial hermetic period treatment, there was no statistically significant difference

($p < 0.05$) at 3 months or 6 months between the moisture content of grains inoculated with storage pests and not inoculated.

Table 1. Moisture content across storage trials, % dry basis (standard deviation).

Treatment	Sampling Instance	iGDSS, 7 Wk IHP	19 L, 3 mo IHP	19 L, 6 mo IHP
Inoculated—10 weevils/kg	Initial	13.6 (0.5) ^{a,1}	13.6 (0.0) ^{a,1}	13.6 (0.0) ^{a,1}
	3 mo	13.1 (0.2) ^{b,1}	13.2 (0.2) ^{b,1}	N/A
	6 mo	14.5 (0.4) ^{c,1}	15.1 (0.7) ^{c,2}	14.8 (0.3) ^{b,1,2}
Non-inoculated	Initial	13.9 (0.2) ^{d,1}	13.6 (0.0) ^{a,1}	13.6 (0.0) ^{a,1}
	3 mo	12.6 (0.9) ^{a,b,1}	12.1 (0.3) ^{d,1}	N/A
	6 mo	14.9 (0.3) ^{c,1}	14.6 (0.2) ^{c,2}	15.7 (0.4) ^{c,3}

Alphabetical superscript indicates significant differences within column; numerical superscript indicates significant differences within rows.

3.2.2. Test Weight

Test weight shifted throughout storage trials with a general decreasing trend (Table 2). Within the 7-week and 3-month IHP treatments, there was no statistically significant difference ($p < 0.05$) in test weight at 3 months or 6 months between treatments inoculated with storage pests and not inoculated. Within the grains which underwent a 6-month initial hermetic period, there was a statistically significant decrease in test weight from initial to 6 months, and the final test weights were not statistically significantly different between inoculated and non-inoculated treatments after six months.

Table 2. Test weight across storage trials, kg/hL (standard deviation).

Treatment	Sampling Instance	iGDSS, 7 Wk IHP	19 L, 3 mo IHP	19 L, 6 mo IHP
Inoculated—10 weevils/kg	Initial	70.1 (0.6) ^{a,1}	69.5 (0.3) ^{a,b,c,1}	69.5 (0.3) ^{a,1}
	3 mo	68.9 (0.5) ^{b,1}	68.5 (0.6) ^{d,1}	N/A
	6 mo	67.5 (1.7) ^{c,1}	67.3 (0.6) ^{e,1}	68.0 (0.6) ^{b,1}
Non-inoculated	Initial	69.8 (0.5) ^{a,d,1}	69.5 (0.3) ^{a,1}	69.5 (0.3) ^{a,1}
	3 mo	70.0 (0.8) ^{a,d,1}	69.9 (0.6) ^{b,1}	N/A
	6 mo	69.1 (1.0) ^{b,c,d,1}	68.8 (0.9) ^{a,c,1}	68.6 (0.9) ^{b,1}

Alphabetical superscript indicates significant differences within column; numerical superscript indicates significant differences within rows.

3.2.3. Broken, Damaged, and Discolored Kernels

The proportion of damaged and discolored kernels increased over time in all treatments, which is expected for storage conditions rising above 28 °C. After an initial assessment of some subsamples, the grain that was stored at harvest moisture content was considered to have an overall damage proportion over 80% and the values were not further quantified, although the initial damage proportion averaged 22%, likely due to high levels of microbial activity. An example of one replicate from each treatment is shown in Figure 3.

Overall, there was higher average damage reported in the treatments with bugs (Table 3). Comparing differences within hermetic treatments, at 6 months, there was no difference in the proportions of broken, damaged, and discolored kernels in the 7-week IHP with and without storage pest inoculation, although there were differences in the 3-month and 6-month IHP. This indicates that in the 7-week IHP treatment, the effects of storage pests were better controlled than in the other systems.

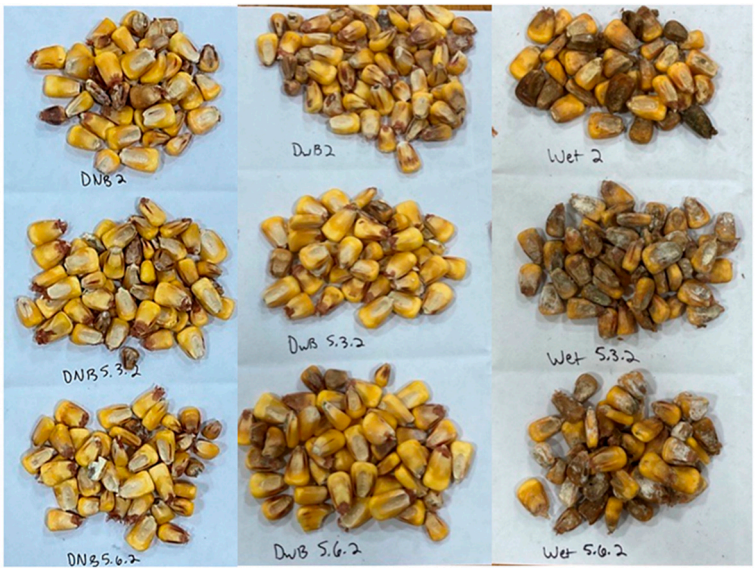


Figure 3. Example of grain appearance after 6-month storage period. Top row: treatments with 7-week IHP. Second row: treatments with 3-month IHP. Third row: treatments with 6-month IHP. L to R: dried, non-inoculated (DNB); dried, inoculated; harvest moisture.

Table 3. Proportion of broken, discolored, and damaged kernels. % broken, discolored, and/or damaged (standard deviation).

Treatment	Sampling Instance	iGDSS, 7 Wk IHP	19 L, 3 mo IHP	19 L, 6 mo IHP
Inoculated—10 weevils/kg	Initial	13.3 (3.8) ^{a,1}	13.3 (3.8) ^{a,1}	13.3 (3.8) ^{a,1}
	6 mo	17.6 (5.7) ^{a,1}	17.3 (2.6) ^{a,1}	32.5 (4.2) ^{b,2}
Non-inoculated	Initial	13.7 (3.1) ^{a,1}	13.7 (3.1) ^{a,1}	13.7 (3.1) ^{a,1}
	6 mo	17.7 (4.9) ^{a,1}	15.7 (4.0) ^{a,1,2}	12.7 (3.0) ^{a,2}

Alphabetical superscript indicates significant differences within column; numerical superscript indicates significant differences within rows.

3.2.4. Germination Rates

Germination rates in dried grains averaged 39.01% at the beginning of the storage trial and 58.2% after six months. The germination rates appear to trend upwards, which is not probable based on the storage temperatures and the generally accepted trend that embryo vigor decreases over time [30]. However, there was high variance between subsamples at each sampling instance (Table 4). Because of the improbability that germination rate would increase over time, it is less advisable to analyze changes between time periods, but the reported values within each time period can be compared.

Table 4. Proportion of germination across storage trials. % germinated (standard deviation).

Treatment	Sampling Instance	iGDSS, 7 wk IHP	19 L, 3 mo IHP	19 L, 6 mo IHP
Inoculated—10 weevils/kg	Initial	43.8 (16.3) ^{a,b,1}	38.7 (9.9) ^{a,b,1}	38.7 (9.9) ^{a,1}
	3 mo	49.1 (13.9) ^{a,1}	41.8 (9.2) ^{a,b,1}	N/A
	6 mo	60.0 (9.8) ^{c,1}	48.4 (19.4) ^{a,1}	55.6 (9.0) ^{b,1}
Non-inoculated	Initial	35.8 (7.5) ^{b,1}	38.7 (9.9) ^{a,b,1}	38.7 (9.9) ^{a,1}
	3 mo	69.3 (12.9) ^{c1}	43.6 (13.0) ^{a,b,2}	N/A
	6 mo	66.4 (10.1) ^{c1}	55.1 (12.4) ^{b,2}	63.6 (4.6) ^{c,1,2}

Alphabetical superscript indicates significant differences within column; numerical superscript indicates significant differences within rows.

3.2.5. Fungal Presence

As an indicator of fungal presence, the log count of colony-forming units (CFUs) per gram of corn was determined across each treatment (Table 5). The colony counts remained stable across the six-month storage period, and there were no significant differences between the initial and final levels across all treatments.

Table 5. Presence of colony-forming units (CFUs) across storage trials. Log CFU/g maize (standard deviation).

Treatment	Sampling Instance	iGDSS, 7 Wk IHP	19 L, 3 mo IHP	19 L, 6 mo IHP
Inoculated—10 weevils/kg	Initial	4.1 (0.5) ^{a,1}	4.1 (0.5) ^{a,b,c,1}	4.1 (0.5) ^{a,b,1}
	3 mo	4.3 (0.6) ^{a,1}	4.2 (0.1) ^{a,1}	N/A
	6 mo	4.2 (0.4) ^{a,1,2}	3.9 (0.2) ^{b,1}	4.2 (0.1) ^{a,2}
Non-inoculated	Initial	3.9 (0.2) ^{a,1}	3.9 (0.2) ^{b,c,1}	3.9 (0.2) ^{b,1}
	3 mo	3.6 (0.6) ^{a,1}	3.4 (0.7) ^{c,d,1}	N/A
	6 mo	3.7 (0.8) ^{a,1,2}	3.7 (0.3) ^{c,d,1}	3.9 (0.1) ^{a,b,2}

Alphabetical superscript indicates significant differences within column; numerical superscript indicates significant differences within rows.

3.3. Oxygen Levels in Hermetic Systems

3.3.1. Oxygen Levels Through Initial Hermetic Period

Oxygen levels in dried grain throughout the initial hermetic periods (IHPs) of 7 weeks, 3 months, and 6 months are displayed in Figure 4, with inoculated treatments shown with solid lines and non-inoculated treatments shown with dashed lines. Across all treatments, low oxygen levels of 2–5% which bring on significant pest mortality were not reached under natural respiration [33]. However, in treatments stored with pests, oxygen rates did drop to lower levels and can be clearly seen in the 7-week and 3-month initial hermetic periods, with five of the six inoculated treatments having lower oxygen levels at the end of the initial hermetic period.

Figure 4. (**a**) Oxygen levels in 7-week IHP, (**b**) oxygen levels in 3-month IHP, (**c**) oxygen levels in 6-month IHP. Day 0 corresponds to 13 December 2023.

Nearly all (8/9 replicates) non-inoculated replicates had very stable oxygen levels throughout the storage trial, while all inoculated replicates showed a decrease in oxygen after sealing, though with differing rates. In the 7-week and 3-month IHP, the oxygen levels fell continuously throughout the IHP, while the 6-month IHP treatments showed more fluctuations. Throughout sampling, it was observed that silicone was displaced or damaged, which could have allowed stretches of up to 4 days where the system had exposure to ambient high-humidity air which could have spurred respiration. On day 94 of storage, silicone was replaced for all 6-month IHP systems, which contributes to the peak across treatments at the next reading on day 98. After re-sealing, all systems inoculated with pests, and the non-inoculated system that had previously experience air intrusion, exhibited a faster drop in oxygen levels than was exhibited in the initial seal.

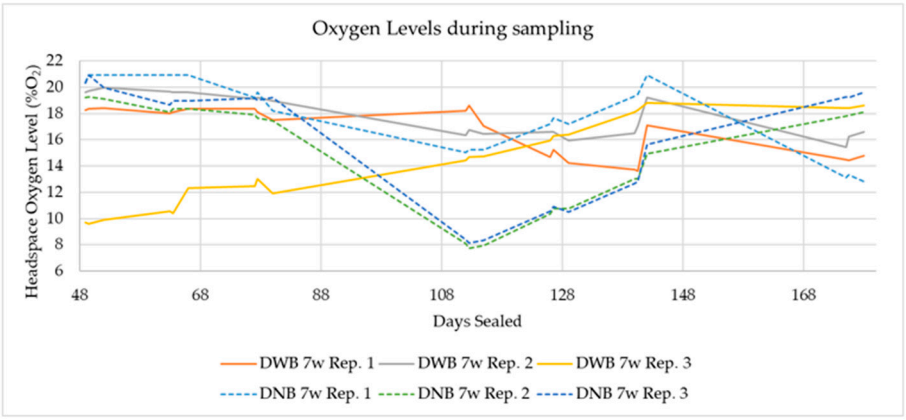
3.3.2. Oxygen Re-Introduction with Periodic Access

The oxygen intrusion into the storage systems was calculated by looking at the oxygen levels immediately before opening, 30 min after sampling, and 72 h after sampling (Table 6). The expected change in oxygen levels was a slight increase 30 min after access because ambient air was allowed to intrude into the systems during sampling. After 72 h, a further increase in oxygen levels in the headspace of the storage containers would indicate oxygen introduced during sampling had diffused throughout the system, while a decrease from pre-sampling might indicate that the introduction of some oxygen allowed for revitalization and resumption of respiration processes by grains, microflora, or storage pests.

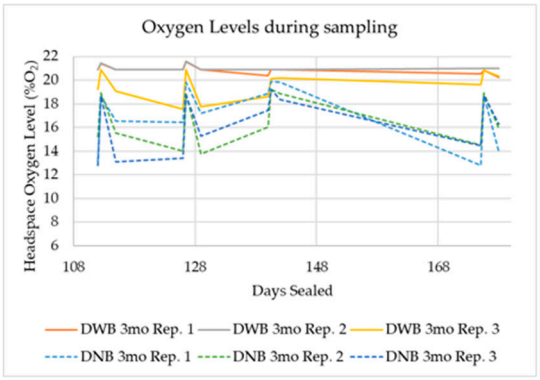
Table 6. Oxygen ingress during sampling across different treatments. Average % O_2 (standard deviation).

Treatment	Sampling Instances (n)	Ingress 30 Min Post-Sample	Ingress 72 h Post-Sample	Average Daily Ingress, 72 h Post-Sample
Inoculated—10 weevils/kg 7 wk IHP	7	0.19 (0.28)	0.28 (0.99)	0.13 (0.37)
Inoculated—10 weevils/kg 3 mo IHP	4	3.86 (1.59)	1.52 (1.20)	0.43 (0.35)
Non-Inoculated 7 wk IHP	7	0.14 (0.27)	0.23 (0.83)	0.10 (0.29)
Non-Inoculated 3 mo IHP	4	0.87 (0.83)	0.24 (0.47)	0.07 (0.17)

In all treatments, the oxygen levels increased slightly in the 30 min after sampling (Figure 5). However, only in the 7-week IHP treatments did oxygen continue to rise from 30 min to 72 h post-sampling. In the 19 L systems, there was a net decrease in oxygen levels from 30 min to 72 h post-sampling. On average, in the iGDSS, the oxygen level was lower 72 h after sampling than immediately before, while in the 19 L systems, the 72 h level was still higher than the pre-sample level.



(a)



(b)

Figure 5. (**a**) Oxygen levels surrounding biweekly sampling in 7-week IHP. (**b**) Oxygen levels surrounding biweekly sampling in 3-month IHP. Systems inoculated with pests in solid lines; non-inoculated systems in dashed lines. Day 0 corresponds to 13 December 2023.

4. Discussion

Throughout the storage trial, the grain moisture content showed an average increase of 1.2%, which is aligned with findings in other hermetic storage trials reporting slight moisture content increases in the range of 1–2% for adequately dried grains [16,19,34–36]. This change can likely be attributed primarily to respiration of the grain itself, as the shift occurred in all treatments, including the ones without intermediate access. While sampling could have introduced ambient air with higher humidity, and insect respiration could have attributed to an increase in moisture, it was found that within each IHP, there was no statistically significant difference in moisture content at 6 months in treatments with and without inoculated *S. zeamais*. This indicates that the presence of storage pests at a density of 10 maize weevils/kg did not impact the grain moisture content under hermetic storage with intermediate access and sampling.

Moisture content is a major parameter determining test weight, and the correlation between increasing moisture content and decreasing bulk density shown in our study falls within the expected range based on studies evaluating test weight and moisture content amongst different corn varieties [37]. Test weight can also decrease when pests directly feed on kernels [38]. Within each IHP, there was no statistically significant difference in test weight between inoculated and non-inoculated treatments, indicating that the presence of storage pests at a density of 10 maize weevils/kg did not impact the grain test weight under this hermetic storage management.

While the iGDSS controlled for the impacts of pests, with no statistically significant difference between inoculated and non-inoculated after 6 months of storage, grains stored in iGDSS had a higher average level of damage than non-inoculated grains stored in the

19 L treatments with longer IHP, although the difference was not statistically significantly different. A longer IHP could effectively control for insect damage because this study relied on natural respiration to deplete headspace oxygen, rather than artificial atmosphere replacement, allowing some insect activity to take place. The re-introduction of some oxygen during repeated sampling could have allowed for resumption of biological activity by the weevils, as some insect life stages are more resilient to low-oxygen environments and population growth could begin again with exposure to increased oxygen levels [15]. To explain the high damage rate of the 6 mo IHP treatment inoculated with insects, we can examine the oxygen levels throughout this storage period (Figure 4c) and see levels never dropped to the 2–5% levels to cause mortality, meaning a population of storage pests could have been active throughout the storage trial [33]. Thus, despite low impacts on other grain quality parameters, the presence of storage pests did cause direct damage to some kernels that was captured in this metric. Some level of visible degradation would be expected in all treatments because of the natural biological breakdown of maize stored at an average temperature range of 24–28 °C, with instances of temperatures reaching up to 50 °C in the greenhouse environment.

It can also be expected that insect damage will influence germination rates, as direct feeding on the seed will impact viability. During their life cycle, adult *S. zeamais* chew through the seed coat to lay eggs inside kernels, and larva will feed on the kernel until it emerges [39]. This study showed an unexpected increase in germination rates, though variation was very high between subsamples. In making comparisons within a single sampling instance, we can see higher germination rates in the iGDSS than in other treatments. There was also no statistically significant difference in the germination rates between inoculated and non-inoculated treatments at 6 months, though there was a difference at three months.

The density of colony-forming units per gram of corn remained stable in all treatments across the six-month storage period, which indicates that when maize is dried to 13.7% before storage, fungal levels are well controlled in hermetic storage systems, even allowing for biweekly access and storage pest infestation at 10 weevils/kg. In another study which compared hermetic and chemical storage management practices to an untreated, non-hermetic control for maize at 13.3% moisture, researchers reported low differences in aflatoxin levels across treatments which were sampled every four weeks [18]. Measuring CFUs alone does not give insight into the fungal species that could have developed during storage, but the aforementioned study and others have shown that hermetic storage can suppress mycotoxin development [18,30,40]. These findings thus support the results of other studies that hermetic storage management must be combined with adequate drying to suppress mold growth [20,30]. Future studies should also investigate parameters relating to dry matter losses and the nutritional quality of grains throughout storage.

Throughout the IHP, oxygen levels in all treatments failed to reach the low levels of 2–5% needed for storage pest mortality. This could be because grain was adequately dried, which reduces biological activity from the grain and its microflora, but also indicates that the weevil inoculation density was not high enough to significantly reduce oxygen in the modified atmosphere. It was also noted that there were some differences in oxygen depletion rates between replicates. Respiration rates of both grain and insects greatly impacted grain moisture content, and slight differences between replicate moisture content or differences in the vigor in storage pest colonies could contribute to the different oxygen consumption rates most notable in the 7-week IHP treatment [21,41]. Among other studies reporting oxygen levels throughout hermetic storage, most only displayed error bars and average values, with error values increasing over time [13,14,20]. Thus, it is not possible to understand how the range of oxygen reduction in replicates in this study relates to other studies. One iGDSS replicate with the highest oxygen depletion rate, indicative of higher levels of pest activity, was correlated with a higher moisture content after the IHP, though not at the beginning of the trial. The moisture and respiration increases observed in this replicate illustrate the damaging cycle of insects being more active and creating higher-temperature and higher-moisture conditions where their population and cumulative

respiration further increase. Future research should include continuous monitoring of oxygen levels and intergranular temperatures and relative humidity to better understand respiration activity.

The high oxygen depletion rate noted in the 6-month IHP after replacing seals on all systems indicates that there were likely increased pest populations in the inoculated treatments, and that the initial pest density of 10 adults/kg was allowed to grow to a higher population because the density did not cause significant drops in oxygen levels through the first three months. The pest density was not quantified in this study, but a similar pattern can be seen in other hermetic trials under access and pest pressure [18].

One study that accessed insect-inoculated hermetic storage systems every 8 weeks and recorded oxygen levels immediately before sampling also reported steeper drops in oxygen as the study progressed, presumably because the initial pest levels were low, at 2 adults/kg [18]. In that study, oxygen rates had only dropped to around 19% after eight weeks of storage but dropped to 6–12% after sixteen weeks [18]. That study also experienced the gradual shift upwards reflected in the 6-month replicates represented in this trial, though we did not access grain every 8 weeks but may have had some slow air ingress [18]. It is generally considered difficult to achieve low oxygen ingress rates in rigid containers, including the plastic 5-gallon buckets used for this system [33].

Once biweekly sampling began in this study, treatments with different access mechanisms followed different trends in the 30 min and 72 h following sampling, with a higher oxygen level in the immediate 30 min followed by a net oxygen level decrease in the top-access 19 L systems compared to the iGDSS. This suggests that the iGDSS allowed less oxygen ingress during sampling, and also reflects that the 19 L systems exposed the entire headspace of the container to the ambient atmosphere during sampling, while the iGDSS had a smaller opening for grain access and a distance of 78 cm from the grain access port to the headspace analysis port. This distance explains why it would take oxygen more time to diffuse to the headspace in the iGDSS. The difference in oxygen levels after 72 h may be caused by the re-introduction of oxygen and resumption of biological activity by the weevils, as some insect life stages are more resilient to low-oxygen environments and population growth could begin again with exposure to increased oxygen levels [15]. This resumption of activity, and a growing population base, could have caused the oxygen rates to decrease to a lower starting point after re-activation. Because of the difficulty of maintaining truly airtight barriers, some researchers have looked at threshold oxygen ingress rates through modeling, lab, and field trials and concluded that rates of 0.05% up to 0.15% O_2/day may be acceptable [33,42,43]. Thus, it is an important performance metric that the rate of oxygen ingress in iGDSS remains below 0.15%/day with sampling, demonstrating the access mechanism allows iGDSS to offer the benefits of modified atmosphere storage even under periodic access, as would be practiced by end-users. Additional research in this area could pursue continuous monitoring and a higher density of oxygen sensors to better understand oxygen diffusion through hermetic systems under disturbance.

5. Conclusions

The differences in grain quality and oxygen intrusion were evaluated in the iGDSS compared to an open-head access system. The iGDSS and open-head systems were evaluated under situations to simulate their potential use scenarios in sub-Saharan Africa, with biweekly sampling to simulate access by subsistence farmers, storing treatments in a higher-temperature and higher-humidity storage chamber in a greenhouse, and inoculating some treatments with 10 adults/kg storage of the pest *S. zeamais*. Across all grain quality parameters evaluated, there was no statistically significant difference between the iGDSS systems with and without inoculated pests after 6 months of storage, suggesting the system was able to overcome the pressures of 10 adult/kg initial pest density. Importantly, though the iGDSS system was accessed biweekly in a high-temperature and high-humidity environment, there was no statistically significant difference in CFUs from the beginning to

the end of the 6-month storage trial, indicating the system controls for fungal growth when used with dried grain.

Regarding oxygen intrusion, which is typically harder to prevent in rigid hermetic storage containers, it was found the iGDSS allowed an oxygen intrusion rate of lower than the recommended threshold of 0.15% O_2/day, at which hermetic systems still suppress pest growth, even when the systems were sampled and grains removed. The open-head access systems allowed higher oxygen intrusion in the 30 min immediately after sampling. In conclusion, storage and access using the proposed access modifications to 208 L drums in the iGDSS can offer benefits to hermetic systems while providing regular access to grains, a necessity for subsistence households.

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