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Hermetic storage: under vacuum, under ambient pressure in bags, or in metal containers - what is most suitable?

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Abstract

Insect mortality in hermetic structures is a function of available oxygen, respiration, temperature, and gas tightness. A vacuum can be drawn, provided a gastight flexible storage containment is used, resulting in the following advantages: 1) the tension of the elastic film on the product shows the quality of the vacuum seal and is proof that no pest can enter; 2) the reduction of interstitial oxygen reduces the probability of insects hatching and penetrating through the film to the outside during the initial phase of storage; 3) the reduction of oxygen below 3% leads to mortality of insect pests and reduces the risk of grain quality degradation by molds. Laboratory tests at 20±1°C and 65±5% RH with samples of 1000 g wheat grain in commercially available vacuum bags and 100 infested grains of various developmental stages of *Sitophilus granarius* (L.) or 30 adults had no survivors at a vacuum of 0.5 bar (50 kPa) when the exposure time reached 5 wk. At ambient pressure and hermetic storage in similar bags, 8 wk were necessary for the same effect. A drawback is that liners for vacuum storage consist of multilayer plastics that require sophisticated production machinery and are not suitable for recycling or natural composting. Hermetic storage at ambient pressure using a PE or PP outer bag with gastight PA or HDPE inner bags does not show if the seal is gastight. Improperly sealed or punctured bags may allow influx of oxygen and thus the deterioration of stored products due to insect activity and microbials possibly causing mycotoxin contamination. Another option is the use of metal containers. Silo bins can be welded into suitable sizes, sealed from above and at the grain outlet, but need a shaded location to avoid condensation or the development of leaks from pressure changes. Underground hermetic storage used by our ancestors adds more safety from pests and cooler storage conditions to this type of storage. The question of which storage type is most suitable still needs to be answered.

Keywords: Hermetic, Vacuum, Moisture content, Pest, Mortality, Prevention, Grain quality

Introduction

As a side effect of global warming, granary weevils (*Sitophilus granarius* L.) hatching from wheat grains in the ear could be witnessed in Germany in the hot and dry summer of 2018. This means that at an average monthly temperature of some 21°C, grain had become sufficiently dry and mature in the field for at least 7 wk. Furthermore, this implies that conditions in Central Europe more and more resemble those in tropical countries where a field infestation with stored product pests has to be expected on a regular basis (Adedire, 2001). Combined harvesting and threshing obviously are not sufficiently abrasive to prevent pests from being carried over into storage. At least in 2018, the observation of hatching weevils in the field coincided with a significant infestation with flour beetles (*Tribolium* spp.), rusty grain beetles (*Cryptolestes ferrugineus* Stephens), flat grain beetles (*Oryzaephilus surinamensis* L.), lesser grain borers (*Rhizopertha dominica* F.), and rice weevils (*Sitophilus oryzae* L.) in freshly harvested wheat grains in the silo bin of a project partner testing acoustic pest detection (Müller-Blenkle et al., 2018, 2020). The presence of a large proportion of rusty red flour beetles (*Tribolium castaneum* Herbst), rice weevils and lesser grain borers supports the notion that Central Europe may increasingly become inhabited by a more tropical stored product fauna.

As we search for improved grain storage methods, we should try to develop a system that controls an initial infestation and allows for sustainable long-term storage without toxic residues or hazards to storage operators. Given the remarkable capacity of stored product insects to find suitable stored products by smell (Adler and Ndomo-Moualeu, 2014), future storages should be insect-proof or more hermetic. Ideally, hermetic structures could prevent an insect attack from outside, and control an existing infestation by suffocation.

Hermetic storage has long been studied as a method suitable for stored product protection (Bailey, 1955; Navarro et al., 1994; Adler et al., 2000; Navarro, 2006). New developments in this area during the last five decades that made it into commercial application are perhaps the bunker storage in Australia, hermetic and vacuum storage in flexible cubes (Navarro and Donahaye, 1976), the Purdue Improved Crop Storage Bags (PICS Bags) (Baua et al., 2014), the development of hermetic silobag-storage (Bartosik, 2012), and the implementation of a gas-tightness standard for silo bins in Australia (AS 2628) using flexible paints for retro-sealing.

Flexible structures depend on the quality of the liners used to provide a gastight seal. Navarro et al. (1994) mentioned that PVC-liners with a thickness of 0.83 mm were permeable to oxygen from the ambient atmosphere by 87 mL $O_2 m^{-2} d^{-1}$. As PVC liners age under sunlight, plasticisers evaporate and some flexibility is lost, but permeability drops to some 50 mL $O_2 m^{-2} d^{-1}$ (Navarro et al., 1994). Oxygen permeability may counteract the insecticidal effect of oxygen depletion. Conversely, CO_2 accumulating inside due to respiration may be lost to the outside through permeable liners. However, a comparative practical on-farm study of Grain Pro Super Grain Bags, PICS Bags, and metal silos in Zimbabwe gave equally good results regarding insect mortality and grain quality (Mlambo et al., 2017).

Vacuum storage reduces the absolute amount of available oxygen at the start of storage, and the resulting anoxia can lead to a better protection of grains. Croft et al. (2012) reported that seeds of tropical plants like amaranth (*Amaranthus cruentus*), moringa (*Moringa oleifera*), pumpkin (*Cucurbita moschata*) or tomato (*Solanum lycopersicum*) could be kept in better quality regarding germination when stored under vacuum alone compared to freezing alone, while the best (but also most costly) results were achieved when both were combined. Already much earlier the insecticidal effect of vacuum against pest insects in tobacco had been described (Bare, 1948).

Navarro and Calderon (1979) studied the effects of low atmospheric pressures on the pupal stages of *Cadra* (*Ephestia*) *cautella*.

Finkelman et al. (2006) studied the efficacy of low pressure (50 mm Hg; 6.67 kPa) against the stored product beetles *Trogoderma granarium*, *Lasioderma serricorne* and *Oryzaephilus surinamensis* at 30°C and 50% RH. They found that eggs were the most tolerant stages, that times to achieve 99% mortality of this stage were between 32 h for *O. surinamensis* and 92 h for *L. serricorne*, and concluded that vacuum treatment might be an alternative to fumigation.

In a project on pest-proof storage of grain, horizontal warehouses were rendered insect-proof by sealing the buildings at the walls and doors (Adler et al., 2013; Adler and Ndomo-Moualeu, 2014, 2015). As an alternative to structural sealing, in a laboratory experiment 1.3 kg samples of wheat were stored under 0.5 bar (50 kPa) vacuum at 20±1°C for different periods of time. A moderate infestation had been simulated in some samples by placing 30 adult granary weevils onto the wheat 1 wk prior to drawing the vacuum. After the shortest exposure time tested (three months) granary weevils were found dead and the grain quality did not differ between infested and un-infested grain (Adler et al., 2016). This was the motivation to test shorter exposure times and investigate how developmental stages of grain insects may react to vacuum treatment. Individuals of the genus *Sitophilus* are known to be quite tolerant to hypoxic atmospheres; late larvae and pupae have been described as most tolerant developmental stages regarding anoxic conditions or modified atmospheres (Annis, 1987; Adler, 1993; Adler et al., 2000). The study described here aimed to identify the effect of vacuum storage of grain on the survival of different developmental stages of the granary weevil *S. granarius*.

Material and methods

Granary weevils and their developmental stages were taken from a weekly culture at 25±1°C. Insect culture: every week approximately 1900 young adult granary weevils (16 mL) were placed onto some 3,000 kernels of fresh uninfested wheat grain with a moisture content of 14±0.3%. After an oviposition period of 3 d the adults were removed by sieving, and the grain was kept in glass jars of 1L covered with cotton cloth held by two rubber bands. Through weekly repetition of this procedure, five developmental stages were produced, while within 6 wk the first weevils started to hatch.

Thirty young adult weevils (up to 2 wk old) were directly placed onto the grain in the vacuum bag. For developmental stages, 100 infested grains from a given weekly culture were filled into a small sachet made of nylon gauze with 0.5 mm mesh size. In order to keep oxygen consumption moderate, only two developmental stages were added to a given bag of grain filled with 1 kg of wheat (m.c. 14±0.3 %). A household vacuum machine combined with a welding station (Professional Vacuum Sealer V300, www.la-va.com) was used (Fig. 1). Vacuum bags were stored at 20°C for different time spans.

The vacuum bags (RS-Vac VL 1815) were commercially available bags (www.la-va.com, Germany) which consisted of four layers of plastic polymers, and were 160 µm thick, 250 mm wide and 400 mm in length.

Results and discussion

Results for the survival of granary weevils after different durations of storage at 20°C in vacuum bags are given in Table 1. Survival in vacuum bags was not found after exposure times of 5 wk or longer. In comparison, when similar bags were not vacuumized, but only sealed hermetically, it took 8 wk until no survivors were found. Results indicate that a vacuum environment causes a stress in granary weevils that may lead to death by lack of energy or water. In order to avoid high costs and excessive plastic waste, vacuum bags should be re-sealable.

Table 1. Comparison between total emergence of surviving developmental stages or surviving adult granary weevils after different durations of vacuum storage (0.5 bar; 50 kPa) or hermetic storage at 20±1°C

Exposure time (wk)	2	3	4	5	6	7	8
Vacuum Storage:							
Eggs	31.7	1.7	0	0	0	0	0
Young Larvae	79.3	49.7	0.3	0	0	0	0
Medium Larvae	32.3	8.3	6.7	0	0	0	0
Old Larvae	64	27.7	3.7	0	0	0	0
Pupae	63	23.3	3.3	0	0	0	0
Beetles	0.3	0	0	0	0	0	0
Hermetic Storage:							
Eggs	85.3	64.3	6.7	0	0	0	0
Young Larvae	91	86.7	61.7	12	0	0	0
Medium Larvae	53.3	25.3	17.7	0	0	0	0
Old Larvae	89	54	12	0	4.3	2	0
Pupae	52.3	31.7	5.3	5.3	0	0	0
Beetles	16.7	0	0	0	0	0	0

Mean values of three replicates

But which development is most promising? Under the focus of sustainability, one-way storage systems such as the Silobag storage and PICS Bags may be ruled out as they produce comparatively more waste and environmental costs including production, transportation and waste management in areas often remote from industrial production and treatment sites.

Fig. 1. Vacuum machine with welding station and vacuumized wheat bag with two nylon gauze cages containing 100 grains with immature stages.

A storage method for a basic food crop needs to be reliable, feasible, and sustainable. The simplest, most decentralized production and maintenance of hermetic storage structures may thus be possible with metal containers and silo bins.

Table 2 compares today's commercially available storage methods to underground hermetic storages found in archaeological sites since about the Iron Ages (800 B.C., Hill et al., 1983). Underground hermetic storages were constructed up to the 1850s when convicts built such cave-like structures in Cockatoo Island as part of the convict establishment in the harbour of Sidney (http://www.environment.gov.au/cgi-bin/ahdb/search.pl?mode=place_detail;place_id=105264). Some countries, e.g., in northern Africa and Asia still seem to use underground hermetic storage to a certain extent.

Table 2. Comparison of storage methods and environmental aspects

Method and resources required	Benefits	Risks and/or disadvantages	Environmental aspects
Bunker storage with low walls; Heavy tarpaulin; Drawn by caterpillars	Hermetic storage of large quantities; Semi-underground storage possible; Multiple use	Hermetic seal difficult; Permeability of liners; May be punctured (man, vertebrates)	Large space needed; Concrete surface/walls; Heavy machinery; Large plastic liners; Use more than once
Hermetic storage in Volcani cubes, Grain Pro cocoons etc., with/without vacuum	Hermetic storage in pre-designed cubes; Gastight seal with zipper; Multiple use	Shape flexible, but not volume; Permeability of liners may be punctured or become leaky	Multi-layer plastics; Full recycling not possible; Multiple use
Hermetic metal silos	Hermetic storage; Multiple use	Hermetic seals endangered by day-night temperatures and solar irradiation; Risk of condensation	Multiple use; Recycling possible
PICs Bag; Woven 60 kg or 100 kg bag with one or two gastight in-liner bags	Hermetic storage on a small farmer's level; Number of bags can adjust to harvest	Improper seal at top possible; Punctures or penetration from inside (insects) or outside (vertebrates, plants)	Plastic waste; Single use/unsustainable
Silo bags; Loading and unloading machinery	Hermetic storage of large quantities; Size flexible	Costly machinery; Protection against vertebrates needed; Single use/unsustainable	Large space needed; Plastic waste; Full recycling not possible
Gastight retro-sealing with white elastic paint; Gastight seal of grain inlet and outlet	Solar reflection; Gastight degree is high; Multiple use	Laborious; Hermetic seal difficult to reach	Paint covered metals; Not recyclable; Multiple use
Vacuum BigBag; Multi-layer liners and vacuum pump needed; May be suspended from rack	Vacuum pressure shows sealing quality; Hermetic storage; Faster pest control from reduced oxygen	May be punctured; Few uses	Plastic waste; Full recycling not possible
Underground hermetic storage	Hermetic storage; Natural cooling; No effect of diurnal temperature changes; No access for pests	Laborious construction; Unloading from above	Multiple use; Recycling possible depending on materials used

Pan et al. (2019) suggest the construction of an underground granary using a rigid steel skeleton and flexible polymers to seal the granary from the outside. The authors state that this method would be more ecologically sound and easier to disassemble compared to structures built from concrete. Thus, underground-hermetic storage still finds interest in modern research. Even today, however, the question of which storage type is most suitable for future grain storage still needs to be answered.

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