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Molecular mechanisms of metabolic resistance in booklice (Psocoptera: Liposcelididae)

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Abstract

The psocids from the genus *Liposcelis* are also named booklice, which are stored-product insect pests. Recently, apparent insecticide resistances have been observed in booklice. Here, we mainly focus on mechanisms of metabolic resistance associated with the three major enzymes, Cytochrome P450 monooxygenases (P450s), Estrases (ESTs), and Gluthione-S-transferases (GSTs) in booklice. We developed four comprehensive transcriptomic databases for four booklice, and a large number of detoxification genes potentially involved in insecticide resistance were identified. Totally, 49, 68, 94 and 82 P450 genes, 31, 37, 35 and 23 GST genes, 21, 19, 34 and 19 EST genes were identified for *L. bostrychophila*, *L. entomophila*, *L. tricolor* and *L. decolor*, respectively. The large number of P450s and GSTs implied that Liposcelis species could potentially develop high level of insecticide resistance. The mRNA expression levels of detoxification genes showed that these genes expressed at all tested stages, but exhibited stage-specific patterns, with the higher expression in adults and elder nymphs. Additionally, mRNA abundances of P450 genes were relatively more abundant in adult females than in adult males. The research on different strains showed that the resistance strain of both *L. bostrychophila* and *L. entomophila* had significantly higher mRNA expression and enzyme activity of the detoxification enzymes than the sensitive strain. The above data indicated that detoxification genes might be associated with metabolism insecticides in psocids.

"Remote Sensing, Predictable Storage of Agricultural Commodities and Advances in Hermetic Storage"

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Abstract

Modified atmosphere hermetic storage, now used in over 115 countries for fumigant-free storage of dry commodities from coffee to rice and maize, has been available for almost three decades. This paper describes the progress in the field use of hermetic postharvest storage systems and of recent innovations in this technology which include the introduction of remote monitoring of temperature, humidity and O_2 or CO_2 levels in large, sealed hermetic containers. Also, introduced in 2018, is the Cocoon Lite™, a 2nd generation multi-tonne container with major improvements in the permeability, weight and cost of high performance, large hermetic storage systems. Early examples of the uses of these innovations and data obtained from their study is expected by year end. The GrainPro EcoWiSe™ is a remote sensing system that enables monitoring of temperature, moisture and oxygen/carbon dioxide levels, thus providing real-time data on the conditions of the stored commodity involved without manual intervention. One (or more) low-cost, remote, wireless sensors/transmitters placed inside sealed. Postharvest hermetic storage units can be read remotely on laptops or cellphones. Data collected and accumulated over time enables development of an "algorithm" for a stored commodity to define an alarm, where the user can be notified immediately of any unsafe humidity or oxygen storage conditions. A substantial advance in large hermetic storage containers known as Cocoons™ is the new Cocoon Lite, a 500:1 improvement in permeability to oxygen as well as a unit weight only 28% of existing Cocoons with the same capacity and a significantly lower cost. The paper also discusses prevention of the public health hazard of exponential growth of aflatoxin levels in conventional postharvest storage such as in rice, maize, and groundnuts; field data is provided on the control achieved through hermetic storage.

Keywords: hermetic, grain storage, aflatoxins, remote sensors, safe storage, seed storage

1. Brief overview of current hermetic storage use for postharvest storage

Over 25-years ago, we saw the first commercial introduction of fumigant-free, hermetic (airtight) postharvest storage for many types of grains and seeds. Where used, this resulted in drastically reduced, multi-month storage postharvest losses of the stored grains and other dry commodities. Hermetic storage to prevent both qualitative and quantitative postharvest losses for periods of one-year (or more) is now used in over 115 countries and takes many forms. Hermetic storage has the further proven benefit of arresting the exponential growth of aflatoxins, a major public health hazard for key commodities, especially in hot, humid climates.

In 2018, a new large multi-tonne storage unit, the Cocoon Lite was introduced to supplement the existing 5 to 1,000 tonne capacity Cocoon for indoor or outdoor use. The Cocoon Lite described further is much lighter, has 500 times lower O_2 permeability and is significantly less expensive than the standard Cocoon.

Various manual means have been used to verify the continued integrity of hermetically sealed postharvest storage of commodities, from sampling to taking measurements with an oxygen analyzer. With the 2018 introduction of remote sensing, continuous monitoring of the container environment is now possible. The capacities of currently available hermetic storage units in current commercial use, typically range from 15kg to as much as 1,000 tonnes.

A 2016 Fintrac/USAID study in Kenya concluded: "Hermetic technologies offer small-scale farming families effective, cost-efficient, insecticide-free methods for on-farm storage." (Fintrac 2016).

2. The principle of hermetic storage and its requirements

The goal of hermetic storage is to create a container sufficiently airtight to allow the total insect respiration rate of infesting insects plus, where applicable, that of the stored commodity itself, is to be greater than the rate of residual infiltration of oxygen through the ultra-low permeability hermetic container surface. To successfully accomplish this goal in small size, man-portable storage containers, a special, coextruded PE plus barrier layer with oxygen permeability of available models of between 1 to 50 cc/ m^2/day is used. In large containers of 1-tonne (or more) capacity, use of a PVC with oxygen permeability of less than 500 cc/m^2/day is typical. This approach, which uses 0.8mm thick modern plastic materials, also requires proper sealing (and unsealing) mechanisms to permit the loading and discharge of commodities.

Because of the larger ratio of volume to surface area, small containers such as man-portable bags need much lower permeability than large containers to reach the same equilibrium between respiration and infiltration of air, and therefore to achieve the same degree of oxygen depletion in the container.

Thus, the principle of successful use of hermetic storage is that insect respiration alone, plus any respiration of the commodity itself as well as microflora activity, can create a modified atmosphere and either approach (or reach) the unbreathable atmosphere levels of 3% oxygen. Somewhat higher oxygen levels can be successful in killing insects when synergistic carbon dioxide levels rise to 12 - 15% or above, primarily, through insects exhaling of CO_2.

In those few instances where insect respiration needs to be supplemented, or where rapid disinfestation is desired (or required), the natural insect respiration process can be supplemented by an adjuvant to reduce the time required to reach LT99. The typical adjuvant is carbon dioxide, or for smaller containers, a smaller commercial oxygen-absorbing sachet. In most instances, an initial dose of 80-90% CO_2 alone will kill the total insect population in approximately 10 days, provided that the final concentration of CO_2 remains > 35% (Navarro, et all, 2012).

3. Introduction of remote sensing

GrainPro EcoWiSe™ was introduced in the first half of 2018 as an alternative to manual measurement or observation of the content of a sealed, hermetic container. The remote sensing technology enables monitoring of temperature, moisture, and oxygen/carbon dioxide levels. Measurements are made wirelessly and information is displayed on a laptop or desktop computer capable of receiving wireless signals. Real-time data on the conditions of the stored commodity are produced without manual intervention.

Data collected and accumulated over time enables development of an "algorithm" for a stored commodity using an alarm setting, where the user and others, can be notified immediately of any preset unsafe humidity or oxygen storage conditions. If any of the preset values being monitored are exceeded, the alarm indicates that an out of control condition exists and requires immediate attention. The algorithm helps as well in predicting the "storability" of the commodity.

One (or more) low-cost, remote, wireless sensors/transmitters placed inside sealed, postharvest hermetic storage units can be read without opening the container and at distances up to 500 meters (and more with a repeater), the small electronic module (Figure 1) placed inside the sealed storage container broadcasts information through a nearby computer to the "cloud". A single, remote receiver communicates with one or more sensors/transmitters placed inside. The sensors weigh a fraction of a kilogram and are powered by a 5-year active battery, A single receiver can handle up to one hundred sensors.

Fig. 1 Wireless sensor/transmitter

Fig. 2 Cocoon Lite™ capacity 5-tonne, PE-based, weight 7.75 kg (Courtesy, GrainPro, 2017)

4. A new class of lightweight, multi-tonne hermetic container

2018 also marked the introduction of the Cocoon Lite, an innovating addition to the widely used, PVC-based hermetic Cocoon. Cocoon Lite is lighter and far more airtight than the Cocoon.

The Cocoon Lite (Figure 2) is composed of an improved, 205µ thick composite material consisting of a special formulation of polyethylene, a compound barrier layer, plus a white, opaque barrier layer, which also adds UV-resistance and strength against penetration by insects. It is designed for both indoor and outdoor use.

Although the 5-year rated life of the Cocoon Lite is significantly shorter than the 15-year life of the existing PVC-based Cocoon, advantages include significantly lower cost and a weight of only 20% of the equivalent size PVC Cocoon. Its permeability to O2 improved to <1 cc/m^2/day instead of the conventional Cocoon permeability of <500/cc/m^2/day. This shortens the time needed to reach an unbreathable atmosphere and low oxygen level.

Because it is much lighter, the Cocoon Lite is easier both the transport and install, and it better protects against the entry of outside humidity, with permeability to water vapor of <2g/m^2/day versus <8g/m^2/day for the PVC-based Cocoon.

First deliveries of the Cocoon Lite took place in the first half of 2018.

5. Hermetic storage for control of exponential aflatoxin growth in storage

The health consequences of high levels of aflatoxins (produced by *Aspergillus flavus* and *Aspergillus parasiticus*) are widely recognized as major health problems, particularly in hot, humid climates. The international community and many individual countries have set strict limits on acceptable levels of aflatoxin – most commonly 10-20 parts per billion (ppb), or even 5 ppb for direct human consumption. In practice these limits are often greatly exceeded or not being monitored at all, causing serious health effects by depressing the human immune system (Williams, et. al., 2004).

In humans, high aflatoxin levels contribute to many health problems ranging from cancer and susceptibility to HIV, to stunting growth among children. In African countries, Dr. Williams cites a sampling survey of several local markets which showed that 40% of the commodities tested had food aflatoxin levels exceeding the international standard of 10 to 20 ppb, putting an estimated 4.5 billion people in developing African countries at risk. (Williams, 2011).

A cross-sectional study conducted in Ghana (Dr. Williams, 2011) showed that the immune systems of recently HIV-infected people had above-median levels of aflatoxins and that “people with a high aflatoxin biomarker status in Gambia and Ghana were more likely to have active malaria.” Small holder farmers were particularly affected: “A major area of neglect and opportunity is foods stored by small farmers for their own consumption. A very common consequence of quality control in markets is for farmers to retain, for their own use, grains that would reduce the price offered in the market place.” Further Williams writes “studies of groundnuts in local storage facilities show a steady increase in (aflatoxin) contamination levels and these differences are observed in the cyclical variation in the biomarkers of rural African people.” (Williams, 2011).

“Hermetic (i.e., airtight) storage devices arrest aflatoxin growth nearly entirely”, according to a 2017 ACDI/VOCA brief, sponsored by the Bill and Melinda Gates Foundation. The report states “This has been substantiated through research in both real-world and controlled settings. Hermetic storage offers tangible hope in mitigating aflatoxin’s blight.” (AflaSTOP, 2017).

Figure 3 shows the relation between the growth of aflatoxin-producing molds and humidity. 80% relative humidity and above is common in many parts of Africa, South America and Asia.

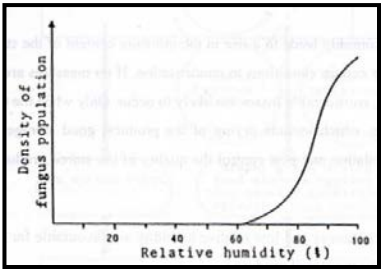

Fig. 3 Effect of relative humidity on mold/fungus density (Harrington, 1972)

Field study results from ICRISAT in Mali (Table 1), show how exponential growth of aflatoxins takes place within months. (Waliyar, et. al., 2013).

Tab. 1 Increased aflatoxin levels in groundnuts during conventional storage in farmers' fields in Mali.

Village In Mali	Aflatoxin content (ppb)		
	At harvest	1 month later in storage	2 months later in storage
Bamba	101.3	168.9	275.5
Gouak	61.4	118.0	174.7
Kolokani	119.2	352.6	400.0
Sido	53.7	93.6	166.2

Another 2013 study from Ruhira, Uganda, by Millennium Villages shows the growth of aflatoxins in conventional storage versus hermetic storage methods and illustrates the major suppression of aflatoxin growth when using hermetic storage versus alternative, conventional storage. (Figure 4), (private communication, 2013).

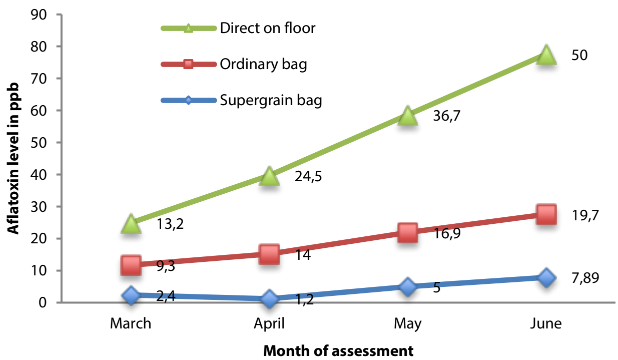

Fig. 4. Comparing aflatoxin concentration over one season in maize stored in conventional and hermetic methods. Millenium Village study in Ruhiira, Uganda (2013).

6. Hermetic storage performance in storing major commodities

Postharvest hermetic storage systems, in addition to contributing to public health through inhibiting aflatoxin growth, dramatically reduce quantitative postharvest losses from insects, rodents and molds. In grains, such as maize conventionally stored for many months, total postharvest losses including storage can (and often) exceed 25%. (Zorya, et. al., 2011).

Field performance of postharvest, hermetic storage systems and the large-scale applicability of Ultra Hermetic storage to preserve dry grains for up to a year, have been studied for several commodities that include: maize, wheat, rice, seeds, coffee, cocoa and ground nuts.

These studies generally have documented reduction of losses using hermetic storage in hot, humid climates to less than 1% per year for up to 1-year. For some commodities, such as coffee and cocoa, the primary goal is preserving premium quality for up to a year without use of refrigeration, pesticide, or fumigants. Examples of results for a few of these key commodities are shown in the following sections, including ground nuts where the injection of CO_2 or oxygen absorbers as an accelerant has been found important.

6.1 Hermetic maize storage

Babban Gona, an integrated contract farming model project, involving 20,000 small farmers in Northern Nigeria, provide farmers with seeds, fertilizer, technical support, financing and take-out in aggregation centers catering especially to quality buyers for high quality/low aflatoxin uses including baby food. Babban Gona features their low aflatoxin levels in its maize. (Figure 6). They report a doubling of farmer yields for maize.

Fig. 5 Storing maize in 150 MT Cocoon at Babban Gona Aggregation Center in northern Nigeria, emphasizing low aflatoxin in their maize (courtesy, Babban Gona, 2017).

According to Babban Gona's records in Oct 2017, the maize losses out of 26,000 tons of the 2016 harvest were an average of 0.003% (about 7 bags out of 250,000 bags stored in 170 Cocoons with 1,500 bags each). (Private communication, Donna Etiebet, Babban Gona, 2018)

A report by Kukom Edoh Ognakossan in Togo compared maize storage in woven polypropylene versus hermetic storage for 150-days with populations of Prostephanus truncates and Sitophilus zeamais. Losses from Sitophilus zeamais were less than 0.5% in hermetic storage versus 19.2% in woven polypropylene. For P. truncates losses in hermetic storage were 6% in hermetic storage versus 27.1% in woven polypropylene. (Ognakossan, I.E., et al, 2013).

6.2 Hermetic rice & rice seed studies

Extensive postharvest studies of hermetic storage of rice and rice seeds (paddy) at IRRI (International Rice Research Institute, Los Banos, Philippines) (Villers and Gummert, 2009), and at PhilRice (Philippines) (Sabio, et. al., 2006)) have shown that rice seeds stored hermetically without fumigants, can be stored for up to a year with negligible loss rates, while maintaining germination rates and vigor. Results are comparable to refrigerated or air conditioned storage. Rice seed, as see in Table 2, can be stored hermetically for six months with germination levels equivalent to air-conditioning or cold room storage without the energy cost or capital investment (Villers, et al., 2006)

In a field study by IRRI, they reported that "in Cambodia, the germination for hermetically stored seeds was 90% after 6 months and 63% after 12 months. In comparison, seed stored in traditional systems had germination of 51% and 8%, respectively" (Villers and Gummert, 2009)

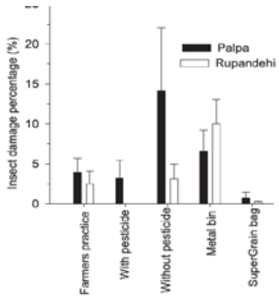

Fig. 7 Insect damage after 6 months in wheat seed versus storage method, Nepal (Devkota et. al., 2017)

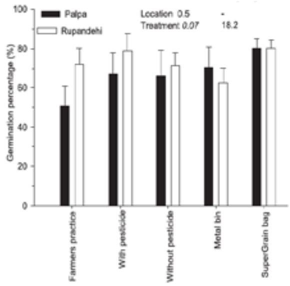

Fig. 8 Comparison of germination rates, wheat seeds in Nepal (Devkota et. al. 2017)

6.3 Hermetic wheat seed storage

An article published in the Journal of Stored Product Research (Devkota, et al, 2017) describes a joint 2017 IRRI and CIMMYT study conducted in Nepal of wheat seed storage measuring quantitative germination performance, insect damage and seed vigor. (Devkota, M., 2017)

The study demonstrated that wheat seed stored in hermetic SuperGrainbags (SGBs®) maintained a lower moisture content, and produced higher seed germination and seed vigor with less insect damage than other storage methods evaluated in the study (Figure 7). It also demonstrated that maintaining wheat seed storage quality is more challenging using traditional storage methods in the Nepalese hills, which have higher rainfall and lower temperature than in the Terai Plains. According to the authors, "the higher germination percentage and lower insect infestation under SGB storage was attributed to maintaining low seed moisture during storage. It is known that every 1% increase in seed moisture content reduces the seed shelf-life by half (Harrington, 1972).

Shown in Figure 7 and Figure 8 from their study showing data on insect damage and germination %, respectively from their study.

Tab. 2 Mean % germination rate of Mestizo 1 hybrid paddy (unmilled) seeds stored using different storage technologies. (Sabio, G.C., et al, 2006)

	Storage time after harvest (months)			
Storage method	**0**	**3**	**6**	**9**
Hermetic	96.2	96.5	93.3	86.2
Cold Room	96.8	97.6	93.0	89.6
Air-conditioned	94.3	94.8	88.1	85.8
Control (unprotected)	92.9	92.9	76.4	74.7

Tab. 3 Mean percent adult insect density1 per kg sample of Mestizo 1 hybrid paddy seeds stored under different storage technologies and durations. (Sabio, G.C., et al, 2006)

Months	Open Storage	Air-Conditioning	Cold Room	Hermetic (5 tons)
0	3.2	8.4	8.4	8.8
3	135	1.6	0	0
6	114	3.0	0	0.4
9	54	3.4	0	0.4
12	27	9.0	0	2.2

6.4 Green coffee storage

In the case of coffee, hermetic bags typically sized 15kg to 69 kg capacity, have become the defacto standard worldwide for the specialty coffee sector.

In 2012, Dr. Flavio Borem's Brazil study concluded "The coffee beans stored in the hermetically sealed packaging predominantly had desirable flavors such as chocolate, vanilla, citrus and red fruits. Conversely, the coffee stored in the jute sacks had predominately undesirable odors such as papery and jute." Also, "The lowest losses were observed when coffee was stored with artificial atmosphere. After 12-months, no differences were observed between vacuum and GrainPro bags." (Borem et. al., 2013)

Variations on hermetic storage of green coffee beans have been studied, including another study in Brazil by Dr. Borem that found a small, but not statistically significant, improvement can be obtained by injecting CO_2 during hermetic storage. (See Table 4). As to vacuum storage, in a different study, Dr. Flavio Borem writes: "This result confirm the thesis that it is possible to maintain coffee quality equal to the quality of vacuum-packed coffee, up to now considered by most coffee importers as the best storage system for specialty coffees". (Borem, 2016).

Tab. 4 Quantitative Value for Coffee Quality after 12-months of storage.
Mean values of the overall score of the coffee beans after 12-months of storage.

Big-bag (one-tonne hermetic)	Position	Score
With CO2	Upper	80.00a
With CO2	Middle	80.80a
Without CO2	Upper	78.09a
Without CO2	Middle	78.06a
Other treatments:		
GrainPro (SuperGrainbag, no CO2)	GrainPro	78.98a
Jute sack alone	Jute sack	73.03b

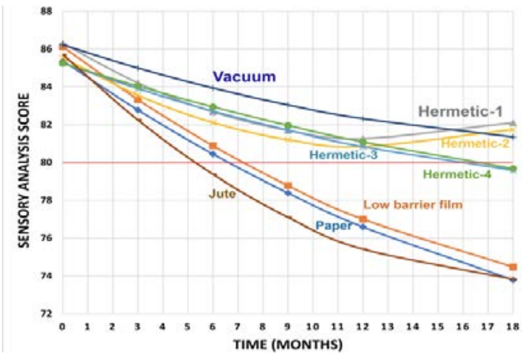

Fig. 9 Adapted from "Evaluation of Packages and Storage Methods for Specialty Coffees", Courtesy of Prof. Flavio Borem, UFLA, Brazil, 2016.

6.5 Hermetic cocoa bean protection

According to a Ghana Cocoa Board report "Experiments were conducted in the year 2008 in Tema, at the research department of the Ghana Cocoa Board with 150 tonne GrainPro Cocoons (for stacked bags of cocoa beans), SuperGrainbags (for 69 kg bags of cocoa), and TranSafeliners™ (gas-tight liner for shipping containers), all showing that the low oxygen/high carbon dioxide atmosphere was able to eliminate the insect population completely in less than two weeks…In conclusion, storing cocoa beans in hermetically-sealed structures inhibits activity of insect pest and mold development; consequently, the FFA deriving from microflora development was inhibited. Most possible that the toxicogenic mycotoxins are also inhibited…" (Jonfia-Essien et al, 2010)

6.6 Special requirements for safe storage of groundnuts

CO_2 injection is currently used in a number of countries for expelling air in order to achieve a faster suppression of mold growth than achieved through respiration alone, which, in the special case of groundnuts, can take 30 days or more to reach 3% oxygen. See table 5.

Tab. 5 Shows the effect of interventions on aflatoxin levels (ppb) in groundnuts for Drobonso Village, Ashanti Region, Ghana, 2014/2015 major season (Appaw, 2016).

	Field (Harvesting Stage)	**Storage Stage + (Poly sac vs Hermetic Bag)**	
Practice	**Aflatoxin level**	**Aflatoxin level**	**% Reduction**
Farmer (conventional)	Not detected	6.61 – 438.79 (133.22 average)	
Improved (hermetic)	Not detected	0.88 – 31.36 (10.89 average)	86 – 99 (95% average)

7. Comparative cost effectiveness data on hermetic storage

Three different examples of cost analysis each for a different commodity, are shown in Table 6, Figure 10, and Figure 11.

The cost effectiveness of utilizing hermetic storage of rice seed versus alternatives was studied at PhilRice in the Philippines, with results as shown below in Table 6. (Sabio et. al., 2006)

Tab. 6. Cost comparison (Philippines) using four storage methods for preserving Mestizo 1 hybrid paddy seeds (all values in US dollars; $1 = 50 Philippine pesos).

	3 months' storage				**6 months' storage**			
Costs	**Control**	**Hermetic**	**Cold room**	**Air-conditioned**	**Control**	**Hermetic**	**Cold room**	**Air-conditioned**
Investment	82,250	1,744	12,820	16,230	82,250	1,744	12,820	16,230
Operating expenses	24,991	504	3,548	3,820	31,086	504	4,196	3,950
Per bag	2.50	2.52	3.55	2.55	3.11	2.52	4.2	2.63

Comparative cost for green coffee storage in figure 10 and comparative cost of storing wheat seed in figure 11.

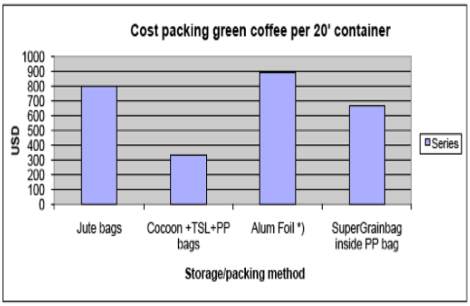

Fig. 10 Comparative Cost Calculations Dorman (VolCafe Kenya) (in USD), (De Bruin et. al., 2012)

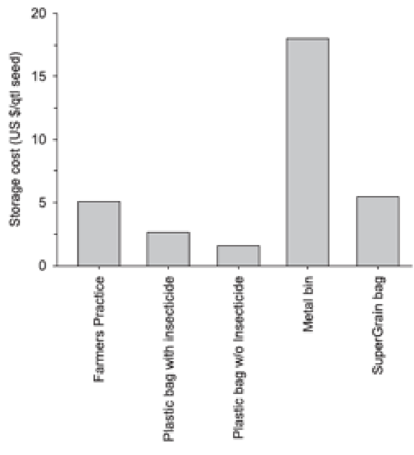

Fig. 11 Comparing storage costs of wheat seeds. Devkota, et al, 2017

8. Range of Hermetic Systems currently in use

The need for hermetic storage varies, in size and form, and in loading/unloading requirements, and thus a variety of such systems are marketed. These range from the traditional Cocoon™, the new Cocoon Lite™ and 1-tonne GrainSafes™ to the light, man-portable 15kg to 90kg SuperGrainbags® (SGBs).

The same material is used in the TranSafeliner™ (TSL), also in Figure 12, which applies the hermetic principle to lining for standard 20- or 40-foot shipping containers. TSLs are used in the coffee, cocoa and spice businesses to prevent deterioration of their high value commodities in intercontinental shipments.

At the other end of the range, 69kg, man-portable storage containers such as the 50 kg cost SuperGrainbag Farm (0.078mm), made of PE with a thinner barrier layer and a higher permeability up to 50cc/m2/day, demonstrate satisfactory performance for storage of non-premium commodities, such as maize or rice crops.

Fig. 12 Examples of different sizes of hermetic storage on-farm and coop storage, ranging from SuperGrainbag liners of 15 – 69 kg and GrainSafes of 1-tonne and Cocoons of 5- to 300-tonnes. (Courtesy of GrainPro, Inc.)

9. Conclusion

More than 25-years ago, the hermetic, postharvest storage once used by the ancients in very large airtight jars sealed with beeswax, was revived in a modern form and became available commercially. Hermetic storage from 15 kg to 1,000 ton capacity is now used within 115 countries worldwide, generally with no more than 1% quantitative losses per year, and highly effective maintenance of quality, including prevention of exponential growth of aflatoxins. Recently, the introduction of remote sensing can largely eliminate the danger of unobserved accidental damage to a hermetic container that leaves a stored commodity unprotected. Also, recently introduced, is the 2nd generation large hermetic container, which has a 500:1 improvement on oxygen permeability and a weight reduction of 75%. The hermetic storage industry continues to grow and provides a variety of products and performance characteristics as specialized needs are addressed.

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Establishing the value of modern seed storage methods for wheat in diverse production ecologies in Nepal

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Abstract

In the developing-country context of Nepal, farmers often incur in seed losses of 15-30% due to improper storage. To evaluate the efficacy and costs of modern storage alternatives, experimental trials were set up among ten farmers each in two contrasting ecologies, i.e. Palpa (hills) and Rupandehi (terai plains) districts of Nepal in 2013. Several wheat seed storage options were contrasted including farmer practices (FP) such as reused fertilizer bags, polythene bags, household metal containers, and mud bins. Modern storage methods that were evaluated included plastic bags (with and without pesticide), metal bins, and hermetic 'SuperGrainbag' (SGB). Seed quality and losses were assessed after six months of storage (May-October) with parameters such as grain moisture content, insect damage, seed germination, and seedling vigor. The overall quality of seed with FPs was lower in the hills than in the terai plains. Among the treatments, SGBs were more effective in maintaining acceptable seed moisture levels, controlling insect damage (<1%), preserving germination (>90% lab, >65% field), and promoting seedling vigor. Metal bins and plastic bags without pesticide had higher insect damage (7-15%) compared to FP and plastic bags with pesticide (2-5%). In terms of storage costs, SGBs were comparable with the farmers' storage methods ($5-6 per 100 kg seed storage). Our findings demonstrate that SGBs are better at maintaining seed quality and more economical than not only FP but also the other modern storage methods evaluated in this study across different production ecological regions in Nepal.

Keywords: SuperGrain bag, seed quality, germination, insect infestation, seed moisture.

Introduction

As a versatile crop, wheat is an essential part of the diet and food trade in many parts of the world (Uthayakumaran and Wrigley, 2010). In Nepal, wheat is the third most important cereal after rice and maize in terms of area and production. Moreover, it is widely adopted across the country with cultivation ranging from 50 to 4000 m in elevation. It shares 16% of the total calorie and 20% of the total protein supplied from plant products in diets of both the hills and plains in Nepal (CBS, 2015). The plains share 55% of the wheat area and contribute 62% to the total production, compared to 45% and 38%, respectively, by the hills (NARC, 2017).

Good quality seed is considered as the most basic and cheapest, yet most critical input for enhancing productivity (Rana, 1997). However, in Nepal, the seed replacement rate for wheat is only 13% (GoN, 2013). Only 15-20% of the total quantity of wheat seed required for planting is supplied by seed producing agencies that have proper storage structures (warehouses) with moderate cooling and periodic drying facilities. The majority of the seed is exchanged among farmers and stored at room temperature in various kinds of storage materials such as plastic or fertilizer bags, and small to medium sized metal bins, with or without pesticides (FGD, 2013). Seeds, being hygroscopic in nature, are prone to changes in moisture content in response to weather, which