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AN INSIDE LOOK AT THE SILO-BAG SYSTEM

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ABSTRACT

The silo-bags are a hermetic type of storage widely adopted. This paper summarizes the results of the effect of silo-bag storage on the commercial quality of corn, soybean, wheat, sunflower, malting barley, canola and beans. The effect of the modified atmosphere on insect population and storage fungi, and recommendations for proper storage conditions in the silo-bags are also presented.

Overall, when dry grain is stored in silo-bag, the CO_2 ranges from 3 to 10% and the O_2 from 18 to 10%. The degree of modification of the interstitial atmosphere increases with the grain m.c. and temperature having typical CO_2 concentration of 15-25% and O_2 of 2-5% for wet grain.

There are few reports of insect presence in silo-bags. Analysis of data indicates that unfavorable environmental conditions negatively affect insect development. Thus, storage in silo-bags under the analyzed climate conditions help to maintain grain without notable insect populations.

When grain is stored in silo-bags at m.c. that would allow for mold development, the mold activity is lower compared with that of normal atmosphere storage conditions. Additionally, grain temperature inside the silo-bag is mainly affected by the ambient temperature. Silo-bags have a high heat exchange rate with the air and soil (double surface/volume ratio than regular bins), so no heat damage is observed, even when wet grain is stored in temperate weathers.

The overall results indicate that dry grain (equilibrium relative humidity below 67%) can be stored in silo-bag for more than six months without losing quality (measured as percentage of mold damaged grain, test weight, germination, fat acidity, and nutritional and organoleptic parameters, among others). When grain m.c. increases, commercial quality could be maintained for up to six months in winter time, to less than three months in summer time. In all cases, maintaining the airtightness of the bag is a key factor for successful storage. A monitoring system for silo-bags based on measuring CO_2 concentration was also developed.

Key words: hermetic storage, modified atmosphere, storage, quality, cereal, oilseeds

INTRODUCTION

The silo-bags are a hermetic type of storage made with a plastic bag, with the shape of a tube, of 60 m long and 2.74 m diameter. The plastic cover is made of three layers (white outside and black inside) with 235 μm of thickness.

Each bag can hold approximately 200 tonnes of grain and with the available handling equipment is very easy to fill. The new generation of high capacity combines found in the silo-bag system is the ideal partner, since the loading capacity of the bagging machine is basically limited to the transportation capacity between the combine and the place where the bag is filled. Several companies also developed machineries to unload the plastic bag transferring the grain directly from the silo-bag to the truck or wagon with a high capacity (more than 180 tonnes/h).

Argentina is the country in which the silo-bag was developed for storing dry grains. Since mid 1990's when it was introduced, the silo-bag system gained rapid adoption in the agricultural and industrial sector. Each year, more than 40% of the total production of the country is stored in the silo-bags (more than 40 million tonnes in year 2011).

Due to the successful experience in Argentina, the silo-bag system is now being adopted in more than 40 countries worldwide, from countries with tropical weather (i.e. Sudan) to countries with cold weather (i.e., Russia).

There was an important development regarding to the bagging (loading) and unloading equipment. The operating capacity of the loading and unloading equipment is higher than 180 tonnes/h. Fig. 1 shows a picture of a typical loading and unloading equipment.

Fig. 1- Images of loading (left) and unloading (right) machines.

A LOOK INSIDE OF THE SILO-BAG

Environment and Relationships

Fig. 2 shows a diagram of the main factors affecting the ecosystem of the silo-bag and the relationship among them. Based on this model, the respiration of grains, fungi, insects and other microorganisms present in the grain ecosystem consume the O_2 and generate CO_2, heat and water. The respiration process also consumes the grain energy sources (starch, oil or protein), which could be quantified as dry matter loss (DML).

The respiration rate is affected by grain type and condition, m.c., temperature, storage time, and O_2 and CO_2 concentrations. These last two factors make a difference between the respiration rate of grains in regular storage structures and hermetic structures.

The temperature of the grain depends on the initial grain temperature (this effect is less important as the storage period increases), the effect of the sun radiation, the heat release from the respiration process, and the transfer of heat with the air and soil. The grain m.c. depends on the initial grain m.c., the entrance of moisture from the outside (through openings after a rain event into broken or poorly sealed silo-bags), and the moisture released from the respiration process. Additionally, due to the day and night temperature differential, some moisture condensation can occur in the top grain layers resulting in a localized spot of wetter grain.

For any particular time, the CO_2 and O_2 concentration in the silo-bag depends on the balance between respiration (consumption of O_2 and generation of CO_2), the entrance of external O_2 to the system, and the loss of CO_2 to the ambient air. The movement of gases in and out of the silo-bags depends on the gas partial pressure differential and the permeability of the system (through openings in the plastic cover, or through the natural permeability of the plastic material to the gases).

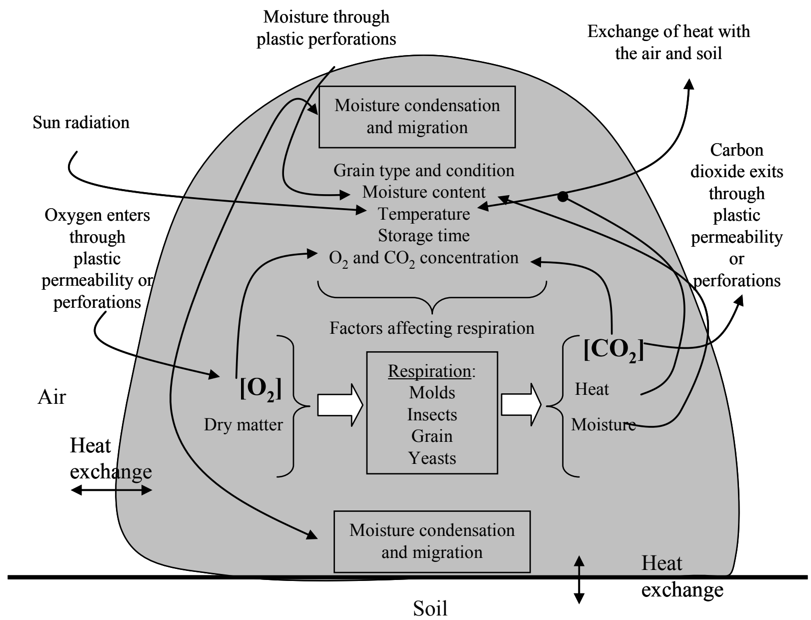

Fig. 2- Section diagram of the silo-bag showing the main factors affecting the grain ecosystem, the relationship among them and with the external environment.

EFFECT OF AMBIENT TEMPERATURE

Bartosik et al. (2008a) indicated that the grain temperature at the surface showed the distinctive pattern of the ambient air temperature, reaching its maximum at noon and minimum during the early morning (Fig. 3). The daily temperature oscillation decreased with the grain depth, being not noticeable after 0.7 m depth. It was also demonstrated that the average grain temperature in the silo-bags followed the pattern of the average ambient temperature through the season.

In a field experiment, silo-bags with wheat were set up during the summer time with grain temperatures close to 40°C. The silo-bag was able to dissipate the heat in the grain to the ambient air and the soil in a couple of months, reducing the grain temperature to less than 17°C by early May (Fig. 3). This could be explained with the relation volume/surface, which is substantially lower for silo-bags (0.7 for a 200 tonnes silo-bag) than for a regular bin of similar storage capacity (1.27 for a 7 m diameter and 9 m height bin of 200 tonnes capacity). On the other hand, soybean and corn, harvested during the fall and winter, were able to maintain the temperature below 17°C until early November. Similar results were reported by Barreto et al. (2012) simulating the effect of ambient conditions on wheat silo-bags temperature in different regions of Argentina.

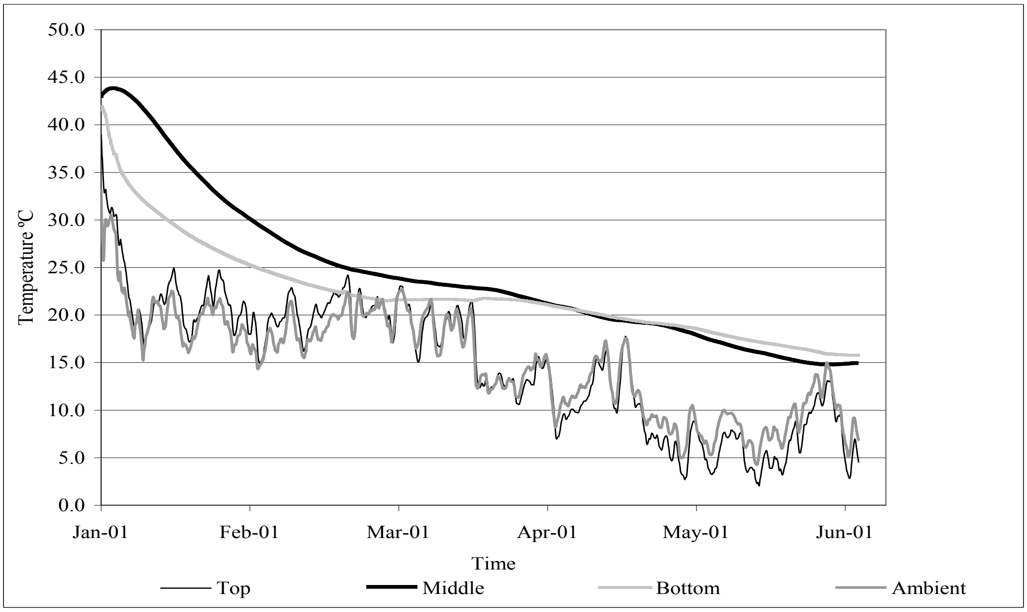

Fig. 3- Temperature pattern at different grain depths (top, middle and bottom) during storage of wheat in a silo-bag from January to June. Source: Bartosik et al. (2008).

Effect of Grain Moisture Content

Since the silo-bag is made of a hermetic plastic cover, no moisture variation should be expected during storage, unless rainwater enters to the bag through openings. Gaston et al. (2009) mentioned that the temperature differential between the top layer and the rest of the bag caused migration of moisture from the core of the grain mass to the top layer, and, to a lesser extent, to the bottom layer. Moisture migration can lead to m.c. rise in some grain layer, increasing the risk of grain spoilage (and grain quality deterioration) in localized areas of the silo-bag. Up to the present, it is not clear the magnitude of the moisture stratification process during storage in the silo-bag. Gaston et al. (2009) considered that grain m.c., grain temperature, grain temperature fluctuation magnitude and storage time affect the magnitude of m.c. stratification.

Darby and Caddick (2007) reported moisture stratification during storage of dry barley (≤ 11% m.c.) under Australian conditions in non-punctured silo-bags. This stratification increased m.c. in the peripheral layer up to 13% over winter, but remained dry over summer with temperatures above 30°C, indicating that the grain could be stored in perfect condition for up to 6 months. On the other hand, Ochandio et al. (2009) did not find m.c. stratification in 12% m.c. barley silo-bags, even after 1 year of storage.

Respiration of Biological Components

Grain, insects, fungi and other microorganisms respire, consuming grain constituents and O_2 from the environment, and releasing to the interstitial environment CO_2, water and heat.

Grain type, m.c., temperature, storage time and O_2 and CO_2 concentrations affect the respiration rate. Most of the factors influencing respiration in silo-bags could be modeled. However, there are no correlations available for predicting respiration rate of grains stored under hermetic conditions (oxygen depleting environments). In order to further improve the modeling of modified and controlled atmospheres it is necessary to generate suitable correlation for predicting respiration in O_2 restricted environments.

Permeability

The transfer of gases between the inside and outside of the silo-bag depends on the gas partial pressure differential and the effective permeability of the silo-bag to gases (permeability of the plastic layer film and perforations). While the permeability of the plastic cover could be measured or estimated based on the characteristics of the plastic material (most of the silo-bags are made of similar materials and have similar thickness), the permeability due to perforations is more difficult to estimate since the size, shape, location and number of perforations differ substantially among different silo-bags.

Plastic Cover

The permeability of the silo-bag plastic cover depends on the thickness and material composition, both set by the manufacturing process. The silo-bag is made of a three layer plastic of 230 to 250 µm thickness, black inside and white outside. The plastic layers are a mixture of high density (HDPE) and low density polyethylene (LDPE). The plastic layer has a differential permeance to O_2 and CO_2. For a silo-bag with an average thickness of 240 µm, Abalone et al. (2011) estimated that the permeance to O_2 was 4.06×10^{-4} $m^3 d^{-1} m^{-2} atm^{-1}$ and to CO_2 was of 1.34×10^{-3} $m^3 d^{-1} m^{-2} atm^{-1}$.

Perforations

Perforations in the plastic cover increase the exchange rate of gases between the inside and the outside. Simulations were performed by Abalone et al. (2011) to explore the effect of structural damage of the silo-bag. It was shown that even a small perforation can significantly change the evolution of gas composition, from 1 percentage point for one perforation of 1 mm diameter per linear meter of a silo-bag, to more than 5 percentage points for one perforation of 10 mm diameter.

The effect of number of perforations on gaseous composition was also investigated. Wheat at 13% m.c. and 25°C stored in a completely airtight silo-bag reached a CO_2 concentration of 6.5% and a O_2 concentration of 12%. One perforation of 3 mm diameter per meter of silo-bag reduces the CO_2 concentration to 4.5% and increases the O_2 concentration to 15%, while 5 perforations per meter resulted in a decrease in the CO_2 concentration to 1.5% and an increase in the O_2 concentration to 19.5% (Abalone et al., 2011).

Oxygen and Carbon Dioxide Concentration

The CO_2 and O_2 concentration in any given time is the result between the respiration rate (depletion of O_2 and generation of CO_2) and the gas exchange rate with the outside (entrance of O_2 and exit of CO_2). Gas concentration data were measured over time for different grains and storage conditions (m.c.) (Fig. 4). Typically, for dry grains, the O_2 concentration equilibrates between 10 and 18%, while the CO_2 concentration equilibrates between 3 and 10%. For wet grains (equilibrium relative humidity higher than 67%) the O_2 concentration drops to 2 to 5%, while the CO_2 rises to 15 to 25%. In some cases, with exceptionally wet grain, the CO_2 concentration can reach values as high as 70% (O_2 close to 0%).

Silo-bags would act as a typical modified atmosphere system when the grain is wet enough to hold biological activity that would consume the O_2 at a higher rate than O_2 is entering to the bag from the outside through the plastic cover. Under this situation the O_2 concentration will drop below the limit at which aerobic respiration starts to be limited. This observation is in agreement with Darby and Caddick (2007) in their comprehensive report made about silo-bags in Australia.

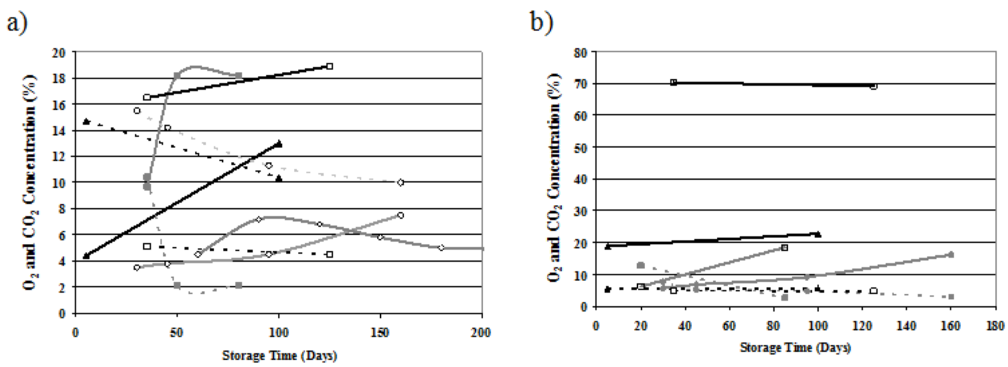

Fig. 4- O_2 and CO_2 concentration during storage of dry (a) and wet (b) grains in silo-bags. Adapted from Bartosik et al. (2008). Legends: solid line, CO_2; dashed line, O_2; ▲, wheat; ■, corn; ○, soybean; □, sunflower; ◊, barley.

The temperature also has a positive effect on the biological activity, but the interaction with m.c. shows that the effect of temperature is higher in wet grain storage than in dry grain storage (Fig. 5). This would imply that dry grain would not hold significantly different biological activity in winter or summer, but storing wet grain could be substantially more challenging (affected by biological activity) in summer than in winter time.

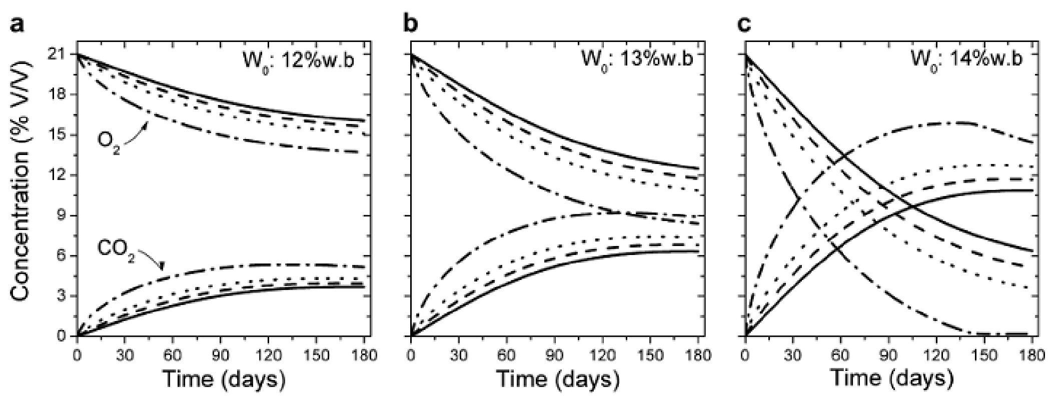

Fig. 5- Predicted evolution of O_2 and CO_2 concentrations during storage from summer (January 1) to winter (July 30) for different initial storage temperatures of grains. Initial grain moisture content: a) 12% w.b; b) 13% w.b; c) 14%w.b. Initial grain temperature:— , 20°C; - - , 25°C; …, 30°C; -·- , 40°C. Source: Abalone et al. (2011) (with permission).

Effect on Quality
Wheat
The storage of dry wheat (12.5% m.c.) during 6 months in a silo-bag resulted with no substantial reduction in the test weight, neither affecting the baking quality parameters (loaf

volume, gluten %, w, etc). When 16.4% m.c. wheat was bagged in January the average grain temperature was of 42°C. The combination of high m.c. and high temperature resulted in a substantial decrease on most of the quality parameters evaluated. Test weight decreased from 78.7 to 77.3 kg/hl, although this decrease did not change the commercial grade of the wheat. Additionally, all the baking quality parameters were negatively affected, making this wet wheat not suitable for flour milling purposes.

Corn

The grain bagged at 14.8% m.c. resulted with a slightly higher test weight after 150 days of storage, while the percentage of damaged kernels increased by 1.3 percentage points (the initial percentage of damaged kernel was greater than 3%). The wet corn samples (19.5% m.c.) resulted with a reduction in the test weight of 2 kg/hl, and a substantial increase of the damaged corn faction of 4.4 percentage points.

Soybean

The soybean bagged at 12.5% m.c. did not substantially modify the test weight and oil percentage of the samples after 150 days. On the other hand, the oil acidity index and the germination were, slightly affected. The wet soybean samples (15.6% m.c.) did not result in effect on the test weight and the percentage of oil, but resulted with an increase in the oil acidity index from 1.7% to 2.3%.

Barley

Malting barley stored dry (below 12% m.c.) for a storage period from 6 to 12 months did not have negative effect on the germination (always remained above 98%). In one study including 56 silo-bags, only 2 resulted with germination test values of 94%, and one with values of 86%. The protein content typically did not change during storage, being the highest change observed of 1 percentage point after 6 months of storage (Ochandio et al., 2009; Cardoso et al., 2010; Massigoge et al., 2011).

Sunflower

When sunflower was bagged at 8.4% m.c. no reduction in oil composition was observed, while the oil acidity index slightly increased from 0.9 to 1.4%. This increase in the oil acidity index did not affect the commercialization standard grade of sunflower, since the oil acidity index limit for the argentine standard is 1.5% until August 31, and 2% thereafter. Thus, storage of dry sunflower (below 11% m.c.) is a safe practice, since the industrial quality parameters were not affected after 150 storage days. Storing of wet sunflower (16.4%) resulted in a reduction of oil composition of 1.3 percentage points (from 47.0 to 45.7%) after 150 storage days, and a more substantial increase in the oil acidity index (0.9 to 3.9%).

Canola

The r.h. in the interstitial air of canola remained below 50% along the entire storage period (canola m.c. of 6%). The m.c., foreign matters and fat values remained unchanged throughout the storage period. The fat acidity increased during storage in 0.7 % points, reaching a final value of 1.4%, but did not represent a commercial quality loss (Ochandio et al., 2010).

Seeds

When seeds are stored with low m.c. (equilibrium r.h. below 67%), no substantial reduction in the germination was observed for wheat (Bartosik et al., 2008a) and barley (Ochandio et al., 2009; Cardoso et al., 2010; Massigoge et al., 2010). In the case of soybean it was observed that when the initial germination values were low, there was a substantial decrease of this parameter during storage, even for m.c. as low as 12.5% (Bartosik et al., 2008a). Additional data showed that when the initial germination value was high (i.e., above 95%), the soybean seed viability did not change during storage when the m.c. was below 12.5%. However, when the seed was stored at a m.c. higher than 12.5%, the number of samples in which a reduction in the germination was observed increased.

Molds and Mycotoxins

In grain ecosystems, the most important abiotic conditions that influence mold growth and mycotoxins production are a_w, temperature, and gas composition. Fungal species involved in the deterioration of stored grain are obligate aerobes, but they can grow under conditions of reduced levels of oxygen, and some species can tolerate high levels of CO_2. Additionally, modified atmospheres also had been reported to have control effect on mycotoxin production at both, high CO_2 concentration and low O_2 concentration (Chulze, 2010).

Pacin et al. (2009) reported fumonisin in corn silo-bags. The contamination levels recorded at the closing of the silo suggest that contamination with molds and fumonisins are more dependent on the grain conditions at the moment of entrance to the silo bags than on the duration of storage.

Castellari et al. (2010) indentified two potential producers of aflatoxins (*A. flavus* and *A. parasiticus*) and a potential producer of fumonisins (*F. verticillioides*) in corn silo-bags with m.c. from 14 to more than 20%, although toxins levels were not tested.

Most of the mold species typically present in grains cannot develop in environments with r.h. below 67-65%, which corresponds with an equilibrium m.c. of 14% in wheat and corn, 12.5% in soybean and 8-9% in sunflower. Under this storage condition in the silo-bag the mold activity is basically stopped, and hence the mycotoxin production.

When storing grain at a m.c. that would support mold growth (equilibrium r.h. higher than 67%), the mold activity and the mycotoxin production would be affected by the atmosphere composition. If the grain is wet, thus the microbial activity would deplete the oxygen rather quickly (few hours), preventing mold damage and mycotoxin production. However, if the grain is slightly wet, the modification of the interstitial atmosphere would be rather slow, and many days (and may be months) would be required to reach the level of mold suppression. Under this condition mycotoxin production could be possible. Additionally, if the grain is wet (high biological activity) but the silo-bag has a low airtight level (i.e., bad sealing of the closing end, perforations, etc), oxygen will enter from the outside allowing mold development and mycotoxin production. The relationship among grain m.c., the effect on biological activity, the resulting CO_2 and O_2 concentration and how this affect the mycotoxin production is yet not fully understood for typical silo-bag storage conditions and more research is needed.

Insects in the Silo-bag

There are relatively few reports of insect infestation of grain stored in silo-bag. Massigoge et al. (2010) reported that insects were observed in 10 barley silo-bags out of 56 monitored. The wheat milling industry, which uses silo-bag for storing dry wheat, indicates that the presence of insects is more frequent during summer time and in silo-bags filled with grain that has been previously stored in regular bins (not coming from the field).

Conditions that Affect Insect Development in Silo-bags

The insect development in silo-bags is limited because: 1) most of the silo-bags are filled with grain coming directly from the field. The presence of stored grain insects in the field is rather scarce, depending on the ambient condition of the harvest time (temperature, r.h.), proximity to storage structures, etc, but most of the time the grain comes form the field free of insects. Additionally, during the harvest operation the grain passes through the combine, then to a truck or wagon and then to the bagging machine, reducing the risk of infestation when compared to grain stored at the elevators. 2) The plastic bag itself comes free of insects, in comparison with regular bins which could be infested prior to the harvest. 3) Once the grain is stored in the silo-bag, the plastic cover acts as a physical barrier, preventing the entrance of insects. 4) The temperature of the grain inside of the silo-bag follows the average ambient temperature throughout the year. Thus, in temperate and cold climates, during the fall and winter the grain temperature will drop below the range of insect activity (15-17°C), reducing substantially their development. 5) When grain is stored with m.c. above the mold activity limit, the O_2 concentration can drop below the 2% and the CO_2 concentration can rise above 20%, creating a lethal environment for insects.

Based on these considerations, the most critical situation that would favor insect development (and damage) in the silo-bags is when the bag is filled with previously infested grain, the grain is stored over summer time (grain temperature between 25 and 30°C), and the grain is too dry to create a lethal atmosphere for insects.

Phosphine Fumigation

Phosphine fumigation in silo-bags has been successfully implemented when insect control is required. Cardoso et al. (2009) showed that applying aluminum phosphine pellets each 5 m along the silo-bag with a dose of 1 g of PH_3 (3 g of aluminum phosphide) per tonne was sufficient to hold 200 ppm during 5 days in the almost entire grain mass. The critical point was the closing end, where a re-application after 3-4 days was recommended. In a similar study using a phosphine dose of 1.5 g m^{-3} in wheat, Ridley et al. (2011) found that complete control of all life stages of *R. dominica* was achieved at all locations in the fumigated silo bags.

Monitoring Grain Quality (CO_2 Monitoring)

The respiration of the biotic components of the grain mass (fungi, insects, and grain) increases CO_2 and reduces O_2 concentrations. Thus, the degree of modification of the gas composition in the interstitial air could be related to the biological activity inside the silo-bag, and can be used as a monitoring tool to detect early spoilage problems (Bartosik et al., 2008b). INTA developed the CO_2 monitoring technology with a private company (Silcheck, Lincoln, Argentina). Trained personnel with a portable CO_2 meter measures interstitial atmosphere CO_2 composition every 6 m along the bag, perforating the plastic cover with a needle (this operation takes less than 10 min for the entire bag). The information is uploaded to a server where the data are automatically analyzed and processed, a storage risk index is elaborated for each environment of the silo-bag, and the storage condition of the silo-bag can be monitored through internet. In case of detecting unsafe storage conditions, an automatic report is sent to the owner of the silo-bag through e-mail, fax or by cell phone SMS.

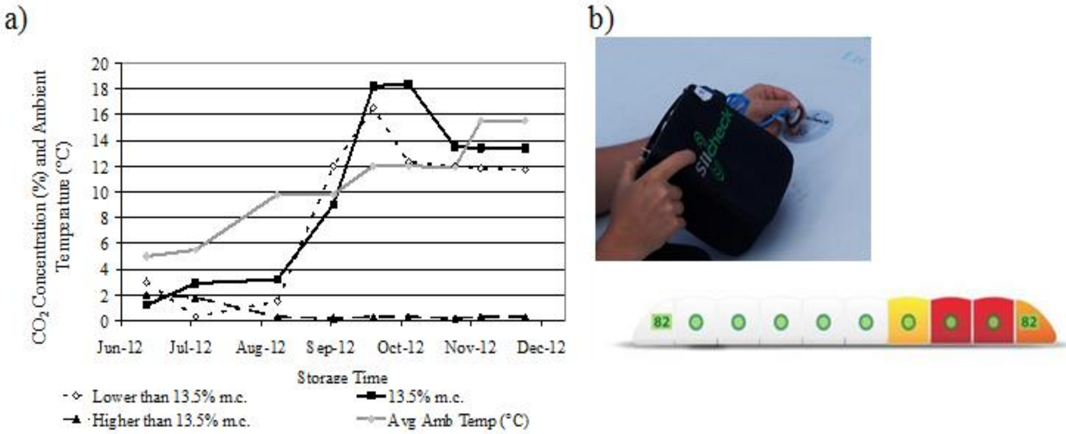

Fig. 6- a) CO_2 concentration during storage of one silo-bag without storage problems (-▲-) and two silo-bags with spoiled grain (‒■‒ and -◊-) with soybean at m.c. around 13.5% (Source: Bartosik et al., 2008b). b) CO_2 meter and internet report with visual information showing in a color scale the storage risk index.

Recommendation for Successful Storage with Silo-bags

The overall results indicate that dry grain (equilibrium r.h. below 67%) can be stored in silo-bag for more than six months without losing quality (measured as percentage of mold damaged grain, test weight, germination, fat acidity, and nutritional and organoleptic parameters, among others). When grain m.c. increases, commercial quality could be maintained from three to six months in winter time, and from one to three months in summer time.

Silo-bags storing dry grain will not create a lethal environment for insects. However, low temperatures during winter in temperate climates will affect insect development. Storing grain at m.c. that can hold mold activity would create a lethal environment for insects, but the storage time will be limited due to effects on grain quality. Phosphine fumigation in silo-bags is a simple and effective insect control methodology.

Prior to set up the silo-bag, the site selection is a key factor. The piece of land should be high and with a slight slope to avoid rain water accumulation that, potentially, could enter into the silo-bag through perforations. A smoothing and leveling operation of the ground should be done. The soil should not have materials that could damage the bottom of the silo-bag during the filling operation, such as stones, residues of the crop, etc. Additionally, sites that are close to trees should be avoided to place silo-bags, since falling branches can damage the bag.

Maintaining a high airtightness level is a key factor for successful storage. Good care should be taken to maintain the plastic cover integrity during the bag filling operation and during storage. It is also critical to make a proper sealing of the closing end. Thermo sealing seems to be the most appropriated technique for ensuring a high airtightness level.

Place the silo-bags in pairs, leaving one open road for the unloading operation before the next pair of silo-bags. With this configuration, any silo-bag could be unloaded at any time (i.e., because a spoilage problem was detected), without having to unnecessary unload an extra bag.

Set up a fence around the silo-bags to keep out the animals, either wild or domestics (i.e., dogs and cats). The fence could be permanent, or made with electrified wires, such as those used for cattle. The wires should be placed at different heights, according to the typical animals of the location.

Some animals, such as birds and rodents, cannot be controlled by a fence. Thus, a rodent monitoring and control program must be implemented. Keeping clean and mowing or spraying herbicide in the silo-bag area will also help to prevent animal activity around the silo-bags.

The silo-bags should be periodically inspected. Any perforation should be properly sealed immediately. Avoid probing the silo-bag, since the patches often get detached. It is convenient to collect grain samples for quality control during the bag filling operation. Monitoring of the grain storage condition should be done by measuring CO_2 concentration, since it does not affect the physical integrity of the bag.

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