Why Oxygen Barrier Film Wins in Silage Sealing & ROI

WHITE PAPER SUMMARY & SOURCES

Product Focus: Viaflex SealFresh® Gold™ Oxygen Barrier Silage Covers

THE BUSINESS PROBLEM:
Oxygen Drives Loss

Even well-packed bunkers and piles are vulnerable at the top layer and shoulders where silage density is lower and air intrusion is highest. Oxygen activates aerobic spoilage microbes, leading to rising temperature and pH, dry matter and nutrient losses, surface mold, feed refusal, and potential livestock health risks.

Why "Standard Plastic" is Not Enough
Standard polyethylene is not fully impermeable to oxygen, so diffusion can continue during storage, especially in peripheral zones. That is why "covering" alone does not guarantee truly anaerobic conditions.

Temperature Also Matters
Oxygen permeability and spoilage pressure increase as film temperature rises. Dark films can run hotter than lighter surfaces, creating a microclimate that favors yeasts and molds. In field observations, black films ran hotter than white surfaces, with reported morning peaks up to 60°F higher versus white films.

The Advantage of Oxygen Barriers
An oxygen-barrier layer changes the physics in covers. Modern oxygen-barrier silage films commonly pair polyethylene with a true barrier resin such as EVOH (ethylene-vinyl alcohol). EVOH delivers very high barrier performance while maintaining strong mechanical properties (puncture resistance, tear resistance, stretch behavior).

Independent research summaries report that, at similar thickness, oxygen barrier films can be $\frac{1}{200}$ the oxygen permeability of standard plastic films.

Additional EVOH co-extruded structures can achieve hundreds of times lower oxygen permeability than earlier generation polyamide-based barriers under standard conditions.

Practical Formats You'll See in the Market

Co-extruded white-on-black sheets with an EVOH layer between PE layers. (single sheet solution)

Thin oxygen barrier films (PE + EVOH) that typically require a second UV-stabilized protective layer because they are not UV-stabilized on their own.

Proof Points for Measurable Loss Reduction

A meta-analysis of 51 comparisons across bunker silos, clamp silos, and bales found oxygen barrier film systems consistently reduced losses and improved stability versus standard PE coverings:

- Top-layer dry matter/organic matter losses (top 4-24 inches):
  - The oxygen barrier (OB) film reduced surface spoilage by 162 lbs per ton compared to standard polyethylene (PE).
- Aerobic stability:
  - 75 hours (PE) vs. 135 hours (OB)
- Baled silage total dry matter losses:
  - Using oxygen barrier film saved 624 lbs of feed per ton

Field research also reported improved fermentation outcomes in commercial bunker silos covered with an oxygen barrier method versus a standard polyethylene system, including lower pH and mold counts and a modeled performance outcome where the polyethylene system delivered 256 lbs per ton less estimated milk yield than the core, while the oxygen barrier system performed similarly to the core.

Bottom Line

Oxygen barrier films shift silage sealing from "coverage" to controlled oxygen permeability, protecting the highest-risk zones at the top, shoulders, and walls where losses are most expensive.

The Economics

Oxygen barrier films are an ROI story, not an upcharge. Research focused on sealing practices notes the economics of proper sealing can be compelling, reporting reduced losses from using an oxygen barrier films returning $8 for every $1 invested in plastic and labor.

When oxygen-barrier systems reduce top spoilage, customers also save labor and time otherwise spent removing and disposing of wasted surface material.

Get the Full Benefit

Oxygen barrier performance is strongest when paired with sound on-farm sealing practices:

- Seal the high-risk zones first:
  Top surface, shoulders, and sidewalls in bunker-style storage where air intrusion is most severe. Sidewall lining plus a tight top seal can make quality along the wall more similar to the core.
- Maintain a tight, weighted seal:
  Weighting reduces billowing and limits air being drawn under the cover. Tires, gravel bags, and other methods are widely used to keep the film tight to the forage surface.
- Protect the barrier layer from UV:
  Thin oxygen barrier films often need a UV-stabilized secondary layer.
- Execution is key:
  Oxygen barrier films reduce oxygen transmission, but results still depend on packing density, edge management, and consistent cover integrity through storage and feed-out.

THE TECHNICAL STORY:

11 Key Takeaways

1. Oxygen drives spoilage, especially on the top and shoulders.

2. Standard polyethylene still lets oxygen in, even when fully covered.

3. Barrier layers dramatically cut oxygen ingress, improving preservation.

4. EVOH is the key barrier, balancing protection and strength.

5. Oxygen barrier films can be hundreds of times less permeable than polyethylene at similar thickness.

6. Top-layer rot losses drops greatly with oxygen barrier films

7. Using an oxygen barrier film returns $8 for every $1 invested in plastic and labor

8. Aerobic stability improves significantly with oxygen barrier films

9. Less spoilage means less labor and waste during feed-out.

10. Performance depends on good sealing habits: tight weighting, clean edges, protected film.

11. SealFresh® Gold™ Oxygen Barrier Silage Covers provides a high-value upgrade

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Advances in Silage Sealing

Thiago F. Bernardes

Abstract

Spoiled silage at the top and shoulders of a horizontal silo is common because of their lower density and higher aeration. Thus, avoiding or reducing aerobic deterioration in the peripheral areas of the silages becomes a key factor for commercial farms. There are two factors that affect the top spoilage: the quality of the plastic film and how well it is held to the forage. The quality of the plastic film is related to oxygen permeability, thickness, and ultraviolet blocking. To hold the sheet to the crop, sidewall plastic associated to gravel bags and used tires have been good alternatives to be used as weights to secure the sheet on the top surface, but many other means can be applied like sidewall disks. Preventing silage losses due to an inappropriate sealing is important, both from nutritional and economic contexts. Proper air sealing produces well-fermented silage and mitigates losses in the upper layer of the silo.

Keywords: plastic cover, aerobic deterioration, dry matter losses, oxygen barrier film, silage storage

1. Introduction

Limiting losses in the upper silage layer is crucial for ensiling process. When no seal is applied, or when the seal is inadequate, air and moisture enter into the silo, affecting the quality of silage; therefore, silage is covered for two primary reasons. The first is to exclude rainfall because precipitation washes organic acids and other soluble feed components from the forage, and the second is to reduce exposure to air.

Oxygen enables various aerobic spoilage microorganisms to become active and to multiply themselves, resulting in aerobic deterioration [1] and substantial economic losses. The deterioration of the silage is indicated by temperature and pH increase, dry matter (DM) and nutrient losses, surface mold growth, and feed refusal by the animals.

Livestock farms can store silage in various ways such as horizontal silos (bunker and stacks), tower silos, bagged silos, or wrapped bales. Several farms prefer horizontal silos due to relatively low construction costs, greater safety compared to tower silos and high work rates for filling and unloading [2]. Nevertheless, their design allows large areas of the ensiled material to be exposed to the environment and prone to spoilage, especially in the upper layer and near the walls [3].

In horizontal silos, during the storage period, a spoiled layer is formed below the sealing sheet, known as "surface waste." Although there is also some evidence that invisible oxidation losses occur throughout the whole mass of silage during the storage period. A large percentage of the silage mass (about 25%) can be within the top 1 m depending on silo size and depth.

The most common material used to seal horizontal silos is the plastic film. The principal function of the film is to seal the forage and allow anaerobic conditions to establish [4]. Plastic films of 150–200 μm thickness have been used for this purpose. Although polyethylene (PE) sheeting has been the most common method used to protect silage near the surface, the protection provided is highly variable and often changes during storage [5]. Thus, the effectiveness of covering methods is very important to limit aerobic deterioration and losses in the large mass being protected.

This chapter presents the main factors related to sealing methods that affect the extent of aerobic deterioration in horizontal silos. Furthermore, the chapter review aims to identify proper management strategies to improve silage quality on commercial farms.

2. Unsealed silos

Along with proper harvesting and filling techniques, it is also equally important to properly cover a bunker silo. Previous studies have demonstrated that the quality and recovery of silage are compromised if horizontal silos are not covered with plastic film.

A study summarized the DM and nutrient losses when bunker and stack silos are not sealed [6]. From 1990 to 1993, the top 0.90 m of silage from 127 horizontal silos was sampled at three sites throughout the silo face. Sampling depths from the surface were 0–0.45 m (depth 1) and 0.45–0.90 m (depth 2). The silos were sealed with a single PE film of black or white-on-black (from 100 to 150 μm thick) secured with tires, sidewall disks or soil.

Losses were higher in bunkers and stacks that were not sealed. Silage locates in the peripheral area of the unsealed silos showed pH values ranging from 4.75 to 8.55, which were typical of spoiled silage. When a plastic film was applied, the organic matter losses in the upper layer (top 0.45 m) were reduced. Silage sealing also reduced spoilage losses in the second 0.45 m.

The aerobic deterioration is initially limited to the top 15–30 cm in an uncovered silo. The reason for this is that aerobic microbial activity is great enough in the upper layer to remove all of the oxygen entering into the crop either by diffusion or by convection. As the readily degradable components of the crop in the top layer are exhausted, the rate of microbial activity declines allowing oxygen to move deeper in the silo and cause deterioration at that level [7].

Economic evaluations indicate that the reduced losses from using a cover return more than $8.00 for each $1.00 invested in plastic and labor to cover a bunker silo [8]. In a 200-t bunker silo (6 m wide by 20 m long by 2.5 m deep), an effective seal to protect the top 1 m of silage can prevent the loss of 100–400 dollars worth silage, depending on the value of the crop. Proper sealing with a plastic cover is therefore essential to reduce losses and prevent microbial deterioration, which may result in the presence of toxins.

3. Lining bunker walls with plastic

A large part of the silage stored in horizontal silos is exposed to air and is prone to spoilage, especially in the upper part near the walls (at the shoulders of the silo), which are difficult to seal properly. A research reported silage DM losses near the surface of bunker silos to be the highest (76%) near the silo wall and the lowest (16%) in the core [9]. Thus, a problem still not fully solved is the connection of the cover to the bunker silos.

The best results are achieved by putting an additional film 1–2 m deep (depending of the silo size) between wall and forage, and then over the forage, before the main sheet is attached (**Figure 1**). The result of this additional effort is that silage quality along the wall is similar as that throughout the silo [10, 16].
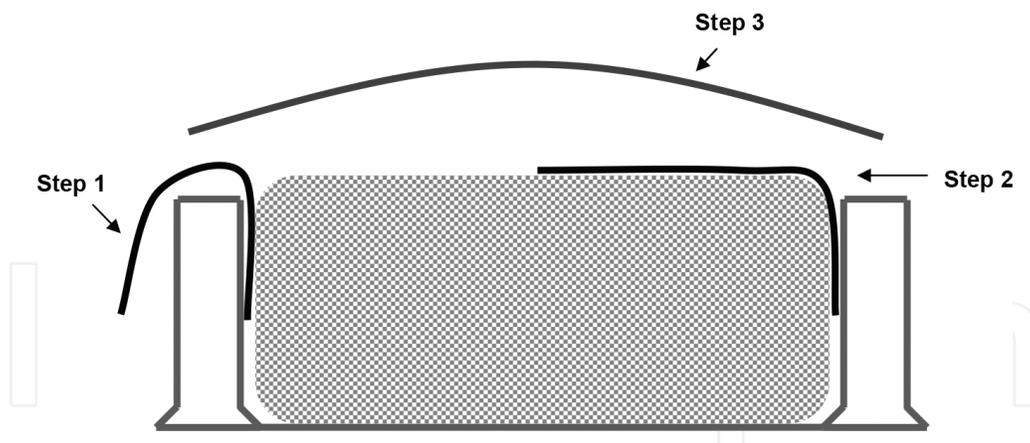
Figure 1. Bunker lining diagram. Step 1 = before silo filling, place a plastic sheet along the length of the sidewall with approximately 2 m of excess draped over the wall; Step 2 = sidewall plastic should lap onto the forage top at the end of filling; and Step 3 = cover the bunker with additional plastic film.

There are limited studies showing the effects of bunker silo sidewall plastic on silage characteristics. A survey in 20 dairy farm bunker silos, 10 without and 10 with sidewall PE plastic, demonstrated that lining bunker wall improves fermentation and produces silage with greater digestibility [11]. Sidewall plastics have more effects on forage preservation; however, it will be addressed in Section 4.2 of this chapter.

4. Plastic film to cover silage

A plastic film to cover silage has to fulfill three essential functions. First, the film should prevent precipitation and damage caused by meteorological effects and animal attack. Second, the film should be UV resistant to resist prolonged exposure to sunlight. Finally, the third function of the silo film is guarantee anaerobic conditions in the silage.

4.1. Color and thickness of plastic film

The color of sheet should affect the amount of air infiltration and subsequent aerobic losses because oxygen permeability into the silage is highly dependent on the temperature of the plastic. Only few data have been published about the thermal effects of covers on the upper silage layers. It is important to emphasize that these surface layers are highly susceptible to poor fermentation because of unsatisfactory packing density and the proximity to the plastic film. Moreover, a microclimate in the upper layer created by the high temperature influences strongly the growth of undesirable microorganisms (yeasts, molds, and aerobic bacteria).

This is consistent with the observations by Bernardes et al. [12], who found highest DM losses and yeast counts when corn silages were sealing with black PE. Black sheet also shows higher temperature in relation to white-on-black film during storage period (**Figure 2**).
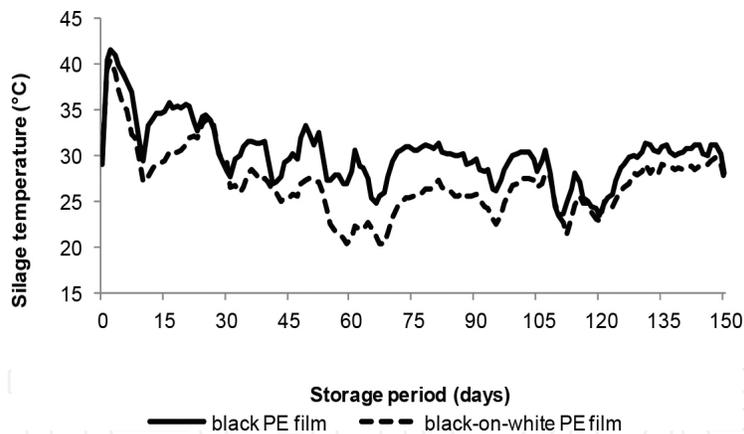

Figure 2. Effects of the color of plastic film on temperature of corn silages during 150 d of storage.

A study reported the effects of the color on the temperature of the film surfaces [13]. The authors found that in the morning hours, temperature peaks were up to 16°C higher for the black film in comparison with the white film. As expected, the highest values were reached at midday, with the black and green colored films showing a very similar thermal behavior. The same applied for the evening hours.

A model to establish the costs of plastic and respiration losses because of air penetration through the film was developed by Savoie [5]. To calculate the optimal thickness, the following parameters were considered: storage period, silage density and DM content, film permeability,

and the relative value of plastic and silage. Polyethylene silage bags of different thickness (100, 150, and 200 μm) did not produce significant differences in losses in 130 d, averaging 0.2% loss/month when perfectly sealed [5]. However, modeling of different film thickness indicated that 100 μm was economically optimum on a stack silo for 3 months storage, 150 μm for 7 months, and 200 μm for 12 months. It is important to emphasize that films with thicker thickness have more puncture and tear resistance than the thin ones.

4.2. Oxygen permeability of plastic films

Air is the major cause of spoilage in silage. Polyethylene is not totally impermeable to oxygen diffusion and thus will not completely prevent oxygen ingress. There is a general agreement, therefore, that low oxygen permeability of the sheets has to be sought.

The first generation of barrier films emerged in the early 2000s when a co-extruded PE-polyamide film was developed for covering horizontal silos [14]. It had 125 μm in thickness and comprised two outer layers of PE with a central layer of polyamide. However, this film showed some problems such as rigidity and fragility what led to less use in farm conditions.

More recently, oxygen barrier (OB) films made with PE and ethylene-vinyl alcohol (EVOH) have been available. Ethylene-vinyl alcohol combines the highest barrier properties with good mechanical characteristics such as puncture resistance, tear resistance, and stretch properties [15].

There are two types of OB films, which are available on European and American market, respectively. The first one is a white-on-black sheet, which is composed by a layer of EVOH between layers of PE during the manufacturing process. The second is a thin film (45-μm-thick PE + EVOH), which needs to be covered by tarp or a second layer of PE during its application in practical conditions. This procedure is necessary because it is not UV stabilized. Originally, the thin OB film was associated with a tarp to protect from UV light as well as from physical damage. However, this type of UV cover is expensive for producers with modest resource availability. Thus, to overcome this problem, a method that combines the thin film with a conventional PE sheet has been created. An experiment was carried out to evaluate the effectiveness of this method for covering corn silage in bunker silos [16]. Two systems were assessed, as follows: the first method comprised a sheet of 45-μm-thick OB film placed along the length of the sidewall before filling, with approximately 2 m of excess draped over the wall. After filling, the excess film was pulled over the wall, and a sheet of PE was placed on top. The second system involved using a standard sheet of 180-μm-thick PE film. Over 2 years, eight commercial bunker silos were divided into two parts lengthwise so that half of the silo was covered with OB and the other with standard system. Oxygen barrier method produced well-fermented silages, which were similar to the central part of the silo (core), whereas PE system showed less lactic acid and greater pH and mold counts compared with core. The estimated milk yield for PE system was 116 kg/ton less than core, as OB system and core were similar (1258 and 1294 kg/ton, respectively), as shown in **Figure 3**. These results and those obtained by Borreani and Tabacco [17] showed a net economic gain when the OB films are used due to both reduced nutrient losses and labor time required to clean the upper layer, even though these films cost more than the PE layer.
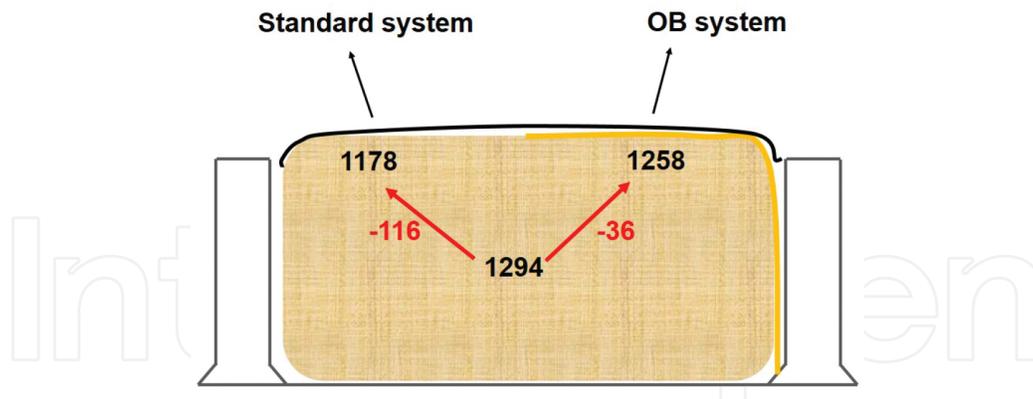
Figure 3. Effects of two covering system on estimated milk yield (kg/ton) of corn silages. Standard system = a single sheet of polyethylene (PE) film; OB system = oxygen barrier film between the silo wall and forage and covered by a second layer of PE film. *Source*: Lima et al. [16].

4.3. Biofilms

An environmental objective is to reduce the quantity of plastic used in agriculture, and there may be opportunity for achieving this by reducing the use of the plastic film for sealing silos. However, horizontal silos produce less plastic wastes than most other systems that use PE film for air tightness. Round bale silage requires at least 5.5 kg of plastic/ton DM. Stack silos use about 1.3 kg of plastic/ton DM, four times less than the round bale silage system [5].

A study was conducted to determine whether the PE film could be replaced with bio-based biodegradable films [18]. A standard 120-μm-thick white-on-black PE film and two different 120-μm-thick biodegradable plastic films were used to produce the silage bags for that experiment. The results of this research showed that the development of new degradable materials to cover silage could be possible. In addition, the authors recommended that further research should be undertaken to improve the blend for enhancing film stability over time and its resistance under outdoor conditions.

5. Weighting the plastic cover

To prevent deterioration in horizontal silos, the common practice is to use plastic film held in place with used car tires. Tires have been widely used because of their low cost and ready availability. In a study reported by Ruppel [19], there was a reduction in the temperature and improved protein availability of hay crop silage when the number of tires per square meter increased. The effects of several covering methods on reduction in the silage losses in the top layer concluded that higher tire density (30 tires per 10 m^2) and sand bags along the shoulders resulted in lower losses [19].

The results of a study on different silage sealing systems were presented by Borreani and Tabacco [20]. A farm bunker silo was covered with a single white-on-black sheet. Half of the

width of the sheet was covered with tires (25 kg/m^2), and the other half was covered with gravel (200 kg/m^2). The silo was opened for summer consumption and had a low feed-out rate (12 cm/d). The results showed that the difference in sealing system affected the temperature in the peripheral areas of the corn silage. The silage covered with tires reached a maximum temperature exceeding 40°C, whereas that covered with gravel did not.

The amount of soil placed on top of the PE plastic cover also has an effect on silage quality. The effectiveness of several sealing strategies that are used in Brazil on reduction in losses in the top layer was tested by Griswold et al. [11]. Covering a black plastic sheet with soil (100 kg/m^2) reduced losses, and this was associated with decreased pH and ash content and lower counts of yeasts. However, most farmers are very reluctant to cover horizontal silos with soil, particularly if the silo is large because they do not believe that the labor and costs involved in covering with soil are reasonable and economical. Moreover, the soil used as a cover can contaminate the silage during unloading. Thus, alternative covering strategies to reduce aerobic deterioration in the peripheral areas of the corn silage in a warm climate were investigated. Three treatments were evaluated: (1) black PE film (control); (2) black PE film plus sugarcane bagasse (10 kg/m^2) over the sheet; and (3) black PE film plus soil (30 kg/m^2) over the sheet [21]. Treatments did not affect the temperatures during the early part of the storage period, but after about 80 d of fermentation, the temperature started to rise in the control silage but not in the others. This can be attributed to the effect of oxygen permeability of the film during a long storage period because the gas transmission rate is reduced by the presence of soil or sugarcane bagasse over the sheet. These results also suggest that the material over the film reduces billowing caused by the wind what affects the amount of air drawn into the silo.

It is important to emphasize that keeping the plastic cover weighed down is critical during the storage and feed-out periods. During the unloading, air can penetrate the peripheral areas of a silo up to 1 m or more beyond the feed-out face [10], especially when the sealing cover is not weighed down or is weighed only with tires, suggesting that, in these situations, daily removal rates should be higher than 30 cm/d to avoid extended aerobic spoilage.

6. Chemical additives on the top of the silos

Especially in warm climates, whole-crop cereal silages such as corn, sorghum, and wheat are susceptible to aerobic deterioration. This is because aerobic yeasts are most active at 20–30°C [22]. Therefore, efforts need to be made to protect the silage near the surface when PE films are used. A research evaluated the application of additives (sodium benzoate and *Lactobacillus buchneri*) directly to the top of the silage and concluded that sodium benzoate applied at a 2 g/kg rate was the most suitable additive to improve the fermentation, reduce the aerobic deterioration, and preserve the nutrients of corn silage at the top of bunker silos [23]. Results from this study showed that the *in vitro* digestibility of the silage at the core and those treated with sodium benzoate were above 640 g/kg, whereas silages untreated and treated with two strains of *L. buchneri* had values close to 600 g/kg (**Figure 4**). According to the authors, under field conditions, the strains may have had their growth affected by high temperatures, and

thus, chemical additives present more robust effects than biological ones when applied at the top.
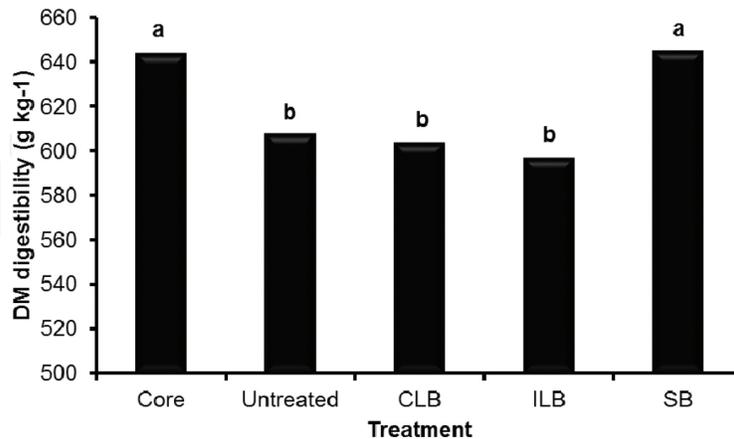
Figure 4. Effects of additives on *in vitro* DM digestibility in different zones of the bunker corn silage. Core = silage in the core of the silo; CLB = silage treated with commercial *Lactobacillus buchneri*; ILB = silage treated with indigenous *L. buchneri*; SB = silage treated with sodium benzoate. *Source*: Da Silva et al. [24].

7. Conclusions

The detrimental effect of air at silage near the surface is a key point to avoid losses of dry matter and quality. To date, no alternative to the use of plastic in covering bunkers or stacks has proven commercially viable for silage producers. Given the widespread use of horizontal silos worldwide, it is vitally important that the film used possesses good oxygen barrier properties as well as good mechanical properties.

In horizontal silos, the plastic needs to be held tightly to the crop. This is usually accomplished with used tires, but many other means can be applied. Besides that, lining bunker walls with plastic improve silage quality along the walls.

The silos' sealing will continue evolving to meet future needs in a conservation of fresh forage, minimize loss and cost, reduce environment contamination, and provide a safe and efficient on-farm feeding system.

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SOURCE:
Meta Analysis of Oxygen Barrier Film
by Grass and Forage Science

A meta-analysis comparing standard polyethylene and oxygen barrier film in terms of losses during storage and aerobic stability of silage

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Abstract

A meta-analysis was undertaken of 51 comparisons of standard polyethylene film with oxygen barrier (OB) film in covering systems for bunker silos, unwalled clamp silos and bales. Mean losses of DM or OM during storage from the top 10 to 60 cm of bunker and clamp silos were 195 g kg^{-1} for standard film and 114 g kg^{-1} for OB film systems (41 sets of data, $P < 0.001$), while mean total losses of DM from baled silage were 76·8 g kg^{-1} for standard film and 45·6 g kg^{-1} for OB film systems (10 sets of data, $P < 0.001$). Top surface silage judged subjectively to be inedible was 107 and 29·6 g kg^{-1} for standard film and OB film systems respectively (5 sets of data, $P = 0.02$). Aerobic stability was 75 h for silage stored under standard film system and 135 h for silage stored under OB film system (11 sets of data, $P = 0.001$). It is concluded that the OB film system reduces losses from the outer layers of silos and from bales and increases the aerobic stability of silage in the outer layers of silos.

Keywords: silage, sealant film, oxygen barrier, losses, aerobic stability

Introduction

The efficient conservation of forage crops as silage, with minimal losses during the storage period, is an important factor in providing ruminant livestock with essential nutrients. Losses can not only reduce the nutritional value of the conserved product but also increase hazards to animal health (Wilkinson, 1999). The failure to implement proper silo management techniques is a source of unnecessary nutrient loss from ensiled crop materials, estimated at 120 g kg^{-1} total quantity of silage made in bunker and clamp silos in the USA between 2007 and 2011 (Bolsen et al., 2012). Dry-matter (DM) losses in the 90-cm layer immediately below the top surface can exceed 300 g kg^{-1} of the original crop ensiled (Holmes and Bolsen, 2009). Standard polyethylene film is not impermeable to oxygen (O'Kiely and Forristal, 2003); consequently, the protection of silage in bunker and clamp silos is variable (Bolsen et al., 1993; Bolsen, 1997).

Oxygen barrier (OB) film ('Silostop', B Rimini Ltd, London, UK) has reduced oxygen permeability compared with standard polyethylene film (Degano, 1999; Borreani et al., 2007; Borreani and Tabacco, 2008a). Wilkinson and Rimini (2002) described the OB film used in their study as triple co-extruded with two outer layers of polyethylene and a central layer of polyamide. Borreani and Tabacco (2012b) described an OB film in which polyethylene, co-extruded with ethylene vinyl alcohol (EVOH), had more than three hundred times lower oxygen permeability than polyamide under standard conditions and at equal thickness. Borreani et al. (2009) and Borreani and Tabacco (2012a) described the development of co-extruded low-density stretch-wrap films for use with baled silage. Stretch-wrap films are typically 25 μm in thickness and are stretched 50% or more on application to the bale. Oxygen-barrier stretch-wrap films have been developed by co-extrusion of polyethylene with either polyamide or EVOH. The physical properties of the films are summarized in Table 1. At similar thickness (e.g. 110–125 μm), the permeability of the OB film to oxygen is about 0·005 that of standard polyethylene film (Table 1). However, there is a range in oxygen permeability both within films, due to changes in ambient temperature (Borreani and Tabacco, 2008a), and also between different sources of film. Carbon black or a proprietary protectant may be added to confer protection from damage by ultraviolet light.

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Table 1 Characteristics of OB and standard polyethylene films for bunker and clamp silos, and stretch-wrap film for baled silage

	Standard film	OB film				Standard stretch-wrap film	OB stretch-wrap film
Thickness (μm)	125[1]	200[2]	45[1]	110[1]	130[2]	25[3]	25[3]
Oxygen transmission rate (cm^3 O_2 m^{-2} per 24 h[4])	1811	846	30	10	8·8	7989	32
Impact resistance (g[5])	300	–	249	518	–	–	–
Force at break (N[5])	–	16	–	–	21	6·4	4·4
Elongation at break MD (%[5])	400	601	500	555	1113	534	733
Elongation at break, TD (%[5])	500	1381	600	540	1176	1015	858

[1]Rimini B., Personal communication. [2]Borreani and Tabacco (2012b). [3]Borreani and Tabacco (2012a). [4]American Society for Testing Materials, ASTM (2013). [5]European Standards (2013).MD, machine direction. TD, transverse direction.

Ultraviolet protectants may also be added to some, but not all, OB films.

Effective sealing of silos and bales can assist in reducing the development of undesirable microorganisms during storage. Counts of moulds and of butyric acid bacteria spores in the peripheral areas of the bunker silos were lower, and aerobic stability tended to be greater for silage stored under OB film than under standard film (Borreani and Tabacco, 2008a). Aerobic instability of silage can be a significant source of loss, especially when the silo is open during the feed-out period. The factors affecting the aerobic stability of silage have been reviewed elsewhere (see review by Wilkinson and Davies, 2012). Key physical and management factors include silage density, permeability and porosity, with the overarching factor being the ingress of oxygen into the silage, not only during feed-out but also during the storage period. A reduction in oxygen permeation through the use of OB sealant film may therefore be expected to have a beneficial effect on the aerobic stability of silage in the outer layer of silos and bales.

In this article, results reported of research in Australia, Brazil, Czech Republic, Estonia, Latvia, Hungary, Italy, Republic of Ireland, United Kingdom and the USA, in which standard polyethylene film was compared with OB film in systems of covering silos and bales, have been drawn together in a meta-analysis (McDonald, 2009) to test the hypothesis that losses during the storage period were lower, and aerobic stability higher, for crops ensiled under OB film than under standard film. The studies covered a range of crops and involved different types and sizes of silo, including wrapped bales.

Material and methods

A total of 51 comparisons of OB film with standard film covering systems were identified in which estimates were made of loss during storage either from the top layer of bunker and clamp (i.e. unwalled) silos or from the total mass ensiled in wrapped bales or in laboratory silos. Thirty-three comparisons were with farm-scale bunker and clamp and eight were with smaller-scale laboratory silos (Table 2). In most of the larger-scale comparisons, silos were divided at the time of covering to produce the two sealant film treatments, which were not replicated. In 11 of the larger-scale comparisons, all with maize silage, samples of silage from the outer layers of each sealant treatment were subsequently exposed to air to determine aerobic stability. Ten further comparisons with ryegrass and lucerne were with baled material; these comparisons were replicated for each treatment within each comparison with individual bales as replicates. In the meta-analysis, each comparison within a data set was considered to be an independent observation.

Used car tyres or woven polypropylene netting is normally placed above the covering film to reduce the risk of damage to the film from wind, birds, animals and (where necessary) ultraviolet (UV) light. The type of protective covering was not stated in 25 comparisons (Table 3). The protective covering was identical for both standard and OB films in 16 comparisons, and in 10 comparisons both film and protective covering were different. In 10 comparisons where both OB and standard films contained a UV protectant, car tyres were used to cover both types of films (Table 3). In 16 comparisons where the type of OB film did not contain protectant from UV light, an additional polyethylene sheet with UV protection was placed on top of the OB film.

Losses from bunker and clamp silos were assessed in the layer immediately below the top surface sealant film. In the case of the comparisons using larger-scale bunker silos, sampling was undertaken in 25 comparisons more than one metre away from the outer walls.

Table 2 Sources of data and treatment comparisons of standard film with OB film.

Reference	Crop	Mean DM of silage (g kg^{-1})	Silo	n	Film thickness (μm)	
					Standard film	OB film
Wilkinson and Rimini (2002)	Grass	162	Laboratory	2	125, 125 + 125	45
O'Kiely and Forristal (2003)	Grass	210	Clamp	1	125 + 125	45 + 125*
Borreani *et al.* (2007)	Maize	340,382	Farm-scale bunker	2	180	125
McDonell *et al.* (2007)	Maize	266	Farm-scale bunker	1	150	45
Borreani and Tabacco (2008b)	Lucerne	611,636,648,652	Bale	4	50, 100, 150, 200†	50, 100, 150, 200†
Kuber *et al.* (2008)	Maize	303,305,255,312	Clamp	4	125	45 + 125*
Amaral *et al.* (2009a,b)	Maize	360	0·5-tonne laboratory	1	200	125
Basso *et al.* (2009)	Maize	309,293	Farm-scale bunker	2	200	45 + 200*
Bernades *et al.* (2009a,b)	Maize	292,305,354	0·5-tonne laboratory	3	171	42 + 171*
Muck and Holmes (2009) and Muck (2011)	Lucerne	Not stated	Farm-scale bunker	4	220	45
Rich *et al.* (2009)	Forage sorghum	245	Farm-scale bunker	1	150	125
Bolsen, K.K., Personal communication	Maize, HMC‡	304,239,274,728‡	Farm-scale bunker	4	125, 190	45
Dolci *et al.* (2011)	Maize	304	Laboratory	1	120	120
Bernades *et al.* (2012)	Maize	320	0·5-tonne laboratory	1	189	121
Borreani and Tabacco (2012a)	Grass, red clover	598,601,585,515, 524,526	Bale	6	100, 150, 250§	100, 150, 250§
Borreani and Tabacco (2012b)	Maize	298,263	Farm-scale bunker	6	200	130
Amaral *et al.* (2012)	Maize	Not stated	75-tonne bunker	2	200	45 + 200*
Lattamae *et al.* (2012)	Grass with red clover	250	Farm-scale bunker	1	150	45
Orosz *et al.* (2013)	Maize	360	Farm-scale bunker	1	125	45
Loucka (2012)	Maize	334,303,339,203	Farm-scale bunker	4	40 + 150	45 + 150*, 55 + 150*

*Single layer of OB film overlaid by a single layer of standard film. †2, 4, 6 or 8 layers of 25-μm film per bale. ‡High-moisture maize grain. §4, 6 or 10 layers of 25-μm film per bale.

In six comparisons, samples were taken near to the outer walls to assess the effect of the two types of film in silage of lower fresh-weight density than that in the centre of the silo. Similarly, in two comparisons with unwalled drive-over piles, samples were taken from the sides of the pile where the density of silage was lower than on the top surface. The depth of sampling below the top surface varied between comparisons from a minimum of 10 cm to a maximum of 60 cm. Top surface losses of DM were assessed in 22 farm-scale comparisons by weighing material into and out of small woven polypropylene bags, which were buried in the top layer of the silo. In 15 comparisons, top surface losses of organic matter (OM) were estimated by determining the concentration of ash in samples of

the crop taken at the time of ensiling and in samples of silage taken after storage using the equation of Bolsen *et al.* (1993). Total loss of DM during storage was assessed in 13 comparisons by weighing laboratory silos or bales at the start and end of the storage period.

Thirty comparisons were made with ensiled whole-crop maize (*Zea mays*), 7 with grass or grass-clover mixtures (predominantly *Lolium* spp.), 8 with lucerne (*Medicago sativa*), 3 with red clover (*Trifolium pratense*), one with high-moisture maize grain and one with forage sorghum (*Sorghum bicolor*).

In the silo comparisons, the standard films varied in thickness between comparisons from 125 to 250 μm in thickness, and the OB films ranged in

Table 3 Protective covering of films, mean density of silage and depth of sampling below the top surface of silo.

	Protective covering of films		Mean density of silage sampled (kg DM m³)	Depth of sampling (cm below the top surface)
Reference	Standard film	OB film		
Wilkinson and Rimini (2002)	PP netting	PP netting	95·1	N/A*
O'Kiely and Forristal (2003)	Car tyres	PE film + car tyres	Not stated	N/A*
Borreani et al. (2007)	PP netting + car tyres	PP netting + car tyres	205	40
McDonell et al. (2007)	Car tyres	PP netting	Not stated	40
Borreani and Tabacco (2008b)	Not stated	Not stated	Not stated	N/A*
Kuber et al. (2008)	Car tyres	Car tyres	Not stated	45
Amaral et al. (2009a,b)	Not stated	Not stated	Not stated	25
Basso et al. (2009)	Not stated	Not stated	Not stated	10
Bernades et al. (2009a,b)	Not stated	Not stated	Not stated	50
Muck and Holmes (2009) and Muck (2011)	Car tyres	PP netting	Not stated	30, 60
Rich et al. (2009)	Not stated	Not stated	Not stated	25
Bolsen, K.K., Personal communication	Car tyres	Car tyres	Not stated	45
Dolci et al. (2011)	Not stated	Not stated	192	N/A*
Bernades et al. (2012)	Not stated	Not stated	Not stated	N/A
Borreani and Tabacco (2012a)	Not stated	Not stated	Not stated	N/A*
Borreani and Tabacco (2008b)	Not stated	Not stated	Not stated	'Upper layer'
Amaral et al. (2012)	None	None	Not stated	'Top zone'
Lattamae et al. (2012)	Car tyres	PP netting	Not stated	30
Orosz et al. (2013)	Car tyres	PP netting	196	30
Loucka (2012)	Car tyres	Car tyres (2 trials), PP netting (2 trials)	Not stated	45, 15 (Trial 4)

*N/A, Not applicable, total loss of DM was assessed. PP, polypropylene. PE, polyethylene.

thickness from 45 to 130 μm (Table 1). In 16 comparisons, a single layer of OB film was overlain by a single layer of standard film, and in 24 comparisons, the OB film was not overlain by an additional layer of standard film. In the ten baled-silage comparisons, both types of stretch film were 25 μm in thickness. The total number of layers of film applied to each bale was varied to give a range of total film thickness (Table 1). Paired comparisons for baled silage were between standard film and OB film of equal thickness.

All 11 comparisons of the aerobic stability of material stored under either standard film or OB film were conducted with ensiled whole-crop maize. Aerobic stability was assessed by exposing samples of silage, taken from the outer layer of the silo, to air at constant temperature and determining the time taken for the temperature of the silage to rise by 2°C above ambient (Ranjit and Kung, 2000).

Silage judged subjectively by visual inspection to have deteriorated to the extent that it was unfit for use as animal feed (inedible silage) was assessed in five comparisons by weighing the discarded material

and determining the DM concentration of representative samples.

Although the data are from many different sources and of different provenances, each sample consists of a comparison between the two films. The paired data were combined in a one-tailed paired t-test to test the hypothesis that within each data set, the mean of the difference between OB film and standard film was greater than zero.

Results and discussion

With the exception of 13 baled silage and laboratory silo comparisons, where total losses were determined by weighing bales and silos before and after storage, the losses described here refer only to the top 10–60 cm of the silo, which comprises a variable proportion of the total mass depending on the absolute height of the silo. Thus, the top 0·5 m is proportionately greater for a silo filled to 1·5 m in height (0·33) than for a silo of equal width and length filled to a similar density to a height of 5 m (0·1). Top-surface-spoiled silage judged to be unfit for use as animal feed

(i.e. inedible) is normally discarded as waste material and, together with material lost from the sides, shoulders and exposed feed-out face, contributes to total storage losses. However, surface-spoiled silage can occasionally be given to livestock. The accidental inclusion of spoiled silage in the ration poses a risk to animal health and can reduce livestock productivity. In an experiment with cattle fitted with ruminal cannulae, silage intake and digestibility were reduced significantly when spoiled maize silage from the top metre of an unsealed silo was mixed, at 0·25 of total silage DM in the ration (0·05 of which was the uppermost 50-cm black slime layer), with unspoiled silage from the same original crop, but stored in a sealed 'AgBag' silo. Inclusion of spoiled silage in the ration appeared to have destroyed the integrity of the forage 'mat' in the rumen (Whitlock et al., 2000).

Woven polypropylene netting, used in some comparisons to cover OB film, may provide less weight per square metre of top surface than would touching car tyres, but would arguably provide better protection of the film from damage by birds and animals. The netting also gives protection from damage by UV light, which car tyres do not.

Mean losses and the range in losses of DM or OM are shown in Table 4 from the top layers of bunker and clamp silos (41 sets of data) and for baled silages (10 sets of data). Also shown are comparable values for inedible silage (5 sets of data) and for the aerobic stability of maize silage (11 sets of data). Losses were numerically higher for silage sealed with standard film than for material conserved with OB film in 43 of the 51 comparisons. In terms of the 41 sets for data for bunker and clamp silos, there was a large range in loss between trials, from −120 to +700 g kg^{-1} and from −89 to +380 g kg^{-1} for crops ensiled under standard film and OB film respectively. Mean losses were 195 g kg^{-1} for standard film and 114 g kg^{-1} for OB film ($P < 0.001$); of these 41 comparisons, 16 comprised OB film overlaid by standard film. Analysis of this subset showed mean losses of 187 g kg^{-1} and 142 g kg^{-1} for standard film and OB plus standard film respectively ($P = 0.023$). These results are in reasonable agreement with estimates made by Bolsen et al. (2012) that the average loss of silage in the original top 75 cm of bunker and clamp silos was 250 g kg^{-1} for standard polyethylene film and 125 g kg^{-1} for OB film.

Figure 1 depicts the losses from the top surfaces of the bunker and clamp silo experiments, the length of each line showing the difference between the two films. Black lines indicate lower losses for OB film and grey lines the converse. The 41 trials are ordered from the lowest OB losses to the highest – note that the first two comparisons are negative. Although the data are quite variable, the frequency of large differences between types of sealant film tends to increase as the overall level of loss increases.

It is possible that the difference in top surface loss between the two types of films depended on the thickness of the standard film, i.e., the greater the thickness of the standard film, the lower the difference in loss. This hypothesis was tested on the comparisons in which standard film was compared with OB film alone (25 comparisons). The results of this analysis are shown in Figure 2. There was no correlation between thickness of standard film and the difference in loss between the two types of films.

Mean losses were higher from bales wrapped in standard film than OB film, averaging 76·8 g DM kg^{-1}
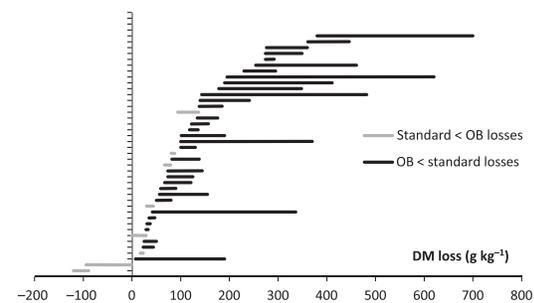

Figure I Bunker and clamp silo comparisons - differences (standard - OB film losses of DM or OM) ordered by OB loss.

Table 4 Losses, inedible silage and aerobic stability of silage in the top surface layer stored under standard film or OB film.

			Standard film		OB film		
	Parameter	n	Mean	Range	Mean	Range	P
Bunker and clamp silos*	Loss of DM or OM (g kg^{-1})	41	195	−120 to +700	114	−89 to +380	<0·001
	Inedible DM (g kg^{-1} total DM)	5	107	59–201	29·6	1·0–39	0·022
	Aerobic stability (h)	11	75·3	0^2 to 184	134·5	48–355	0·001
Baled silage	Loss of DM (g kg^{-1})	10	76·8	43–123	45·6	23–75	<0·001

*Includes drive-over piles and laboratory silos. ^{2} Material already deteriorated at the start of assessment.
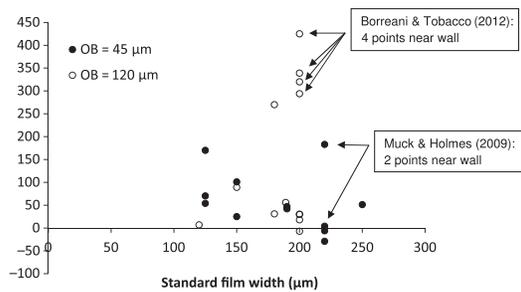
Figure 2 Difference in DM losses (standard − OB g kg⁻¹) for standard film compared with OB film alone.

and 45·6 g DM kg⁻¹ for standard film and OB film respectively (P < 0·001). Borreani and Tabacco (2008b, 2012a) found that losses were related to both type of film and also to the number of layers of film applied to the bale. They also found that the number of layers of OB film potentially could be reduced compared with standard film without adversely affecting silage quality. Although OB film has a greater unit cost than standard film, the value of the silage saved by sealing with OB film may produce a net economic benefit, as demonstrated by Borreani and Tabacco (2010) and Bolsen et al. (2012).

Mean inedible (i.e. mouldy or discoloured) silage discarded from the top layer of the silo was lower for silage stored under OB than for that stored under standard film (29·6 v 107 g DM kg⁻¹, P = 0·02). Wilkinson and Rimini (2002) noted that there was no visible mould development at the top surface of silage stored under OB film, while there was visible mould development to 9·3 and 15·3 cm below the top surface of the silo for silage stored under standard film of 250 and 125 μm thicknesses respectively. Borreani and Tabacco (2008a, 2012b) and Orosz et al. (2013) recorded lower counts of moulds in the top layer of whole-crop maize stored in bunker silos sealed with OB film compared with standard film. The implications are that less labour is likely to be needed in removing wasted material from the top surface of silos and that the development of aerobic spoilage organisms at the exposed silo feed-out face may be reduced.

There was a wide range between comparisons in the aerobic stability of silages stored under OB film and standard film, most likely reflecting differences in crop characteristics, ensiling techniques, fermentation products and silage densities (Wilkinson and Davies, 2012). Mean aerobic stabilities were 75 h and 135 h for silage stored under standard film and OB film respectively (P = 0·001). The difference in aerobic stability between silage stored under the OB and standard covering systems ranged from 3 to 177 h

(Figure 3). It is likely that this wide range reflected differences between trials in crop and microbial composition.

The mean aerobic stability of silage in the uppermost layer stored under OB film was 60 h (2·5 d) greater than comparable material stored under the standard film covering system. This finding is of practical value, especially when the speed of removal of silage from the exposed silo face is relatively slow, in warmer seasons and in tropical climates when ambient temperature and relative humidity are elevated. Improved aerobic stability is probably a reflection of slower development of yeasts and moulds (Orosz et al., 2013) and Acetobacter pasteurianus (Dolci et al., 2011) due to restricted oxygen ingress into the outer layer of the silo prior to full exposure of silage to air at feed-out.

The data reported in this article are of variable provenance, but they are linked by the fact that each individual study is itself a comparison of standard film with OB film. Many studies were unreplicated farm-scale experiments with no information of variation between treatments such as standard errors. Comparisons were made on the basis of the reported mean values. However, inasmuch as each comparison has its own control, the use of a paired t-test to compare the ensemble of results is considered to be both a valid and useful way of assessing the overall benefit of OB film relative to the standard film covering system.

Conclusions

The use of an OB film covering system reduced losses in the top layers of bunker and clamp silos, and in baled silage, compared with standard polyethylene film, on average by 42%. Although only assessed in five comparisons, the proportion of silage judged to be inedible by livestock was also reduced for the OB
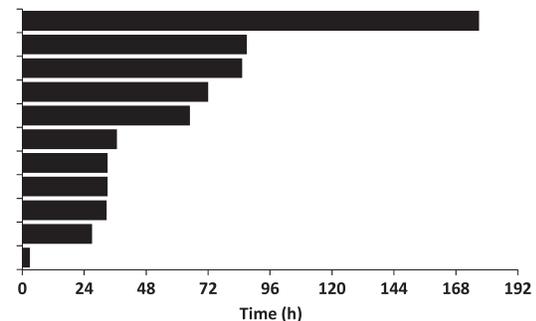
Figure 3 Aerobic stability of maize silage: difference between standard and OB film (n = 11).

compared with the standard film covering system. Although the range in values was high between comparisons, the aerobic stability of the uppermost layer of silage stored under the OB film was higher than that of comparable silage stored under the standard film covering system by an average of 2·5 d.

Acknowledgment

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