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

J. M. Wilkinson* and J. S. Fenlon†
*School of Biosciences, University of Nottingham, Sutton Bonington Campus, Loughborough, UK,
†Department of Statistics, University of Warwick, Coventry, UK

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, $P < 0{\cdot}001$), 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, $P < 0{\cdot}001$). 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, $P = 0{\cdot}02$). 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, $P = 0{\cdot}001$). 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.

Correspondence to: Professor J. Michael Wilkinson, School of Biosciences, University of Nottingham, Sutton Bonington, Loughborough, Leicestershire LE12 5RD, UK.
E-mail: j.mike.wilkinson@gmail.com

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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.

Reference	Protective covering of films		Mean density of silage sampled (kg DM m^3)	Depth of sampling (cm below the top surface)
	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 ($P < 0{\cdot}001$); 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 ($P = 0{\cdot}023$). 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}

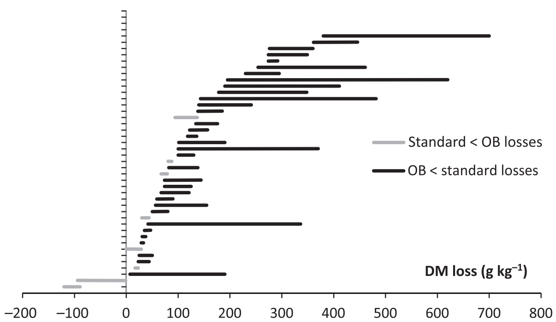

Figure 1 Bunker and clamp silo comparisons - differences (standard - OB film losses of DM or OM) ordered by OB loss.

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

	Parameter	*n*	Standard film Mean	Range	OB film 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.

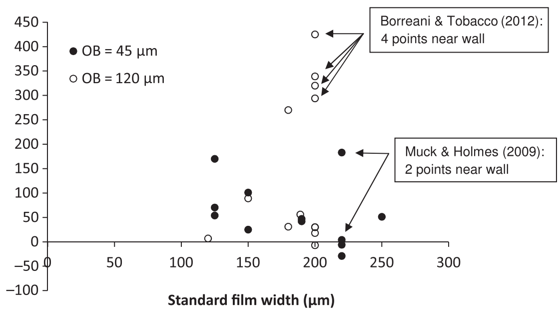

Figure 2 Difference in DM losses (standard – OB g kg^{-1}) for standard film compared with OB film alone.

and 45·6 g DM kg^{-1} for standard film and OB film respectively ($P < 0{\cdot}001$). 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}, $P = 0{\cdot}02$). 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 ($P = 0{\cdot}001$). 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

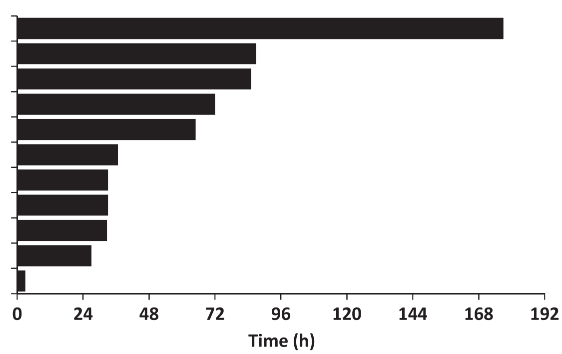

Figure 3 Aerobic stability of maize silage: difference between standard and OB film (n = 11).

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.

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