# NEW CONCEPTS ON BALED SILAGE

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## Introduction

Throughout the world, forage crops are harvested as silage on intensive dairy farms to reduce feeding costs. Among the various silage conservation methods, wrapped bales are commonly used in Europe to preserve the quality of rotational and perennial grass and legume forages (Wilkinson and Toivonen, 2003; McEniry *et al.*, 2007) and have been gaining popularity in the US over the last decade (Han *et al.*, 2006; Arriola *et al.*, 2015). Silage in wrapped bales offers advantages over hay production, such as a more flexible harvest date, less weather dependency and a greater flexibility in ration formulation (Savoie and Jofriet, 2003; Shinners *et al.*, 2009a). Big bale silage is now a well-established conservation system for storing excellent quality forage, and can provide an opportunity to maintain the high feeding value of young herbage (Forristall and O'Kiely, 2005). The making of big bale silage involves several mechanical treatments, ranging from harvesting to storage, to achieve high quality forage in terms of nutritive value and hygienic characteristics. Baled silage is often made from herbage that is wilted more extensively and undergoes more limited fermentation than conventional bunker silage, in order to reduce the number of bales per hectare, the plastic consumption and the costs; moreover, it can be more convenient when fed to animals (Han *et al.*, 2006; McEniry *et al.*, 2007; Tabacco *et al.*, 2013). Unfortunately, the increased dry matter (DM) content also tends to increase fungal growth in wrapped forages (O'Brien *et al.*, 2008; Tabacco *et al.*, 2013), thus increasing hygienic issues as well as the risk of mycotoxicosis (O'Brien *et al.*, 2007; McElhinney *et al.*, 2016) and *Listeria* contamination (Fenlon *et al.*, 1989; Nucera *et al.*, 2016). Even though the baled silage system is based on a well-established procedure, the fact that the incidence of mold spoilage can be relatively high in baled silage (O'Brien *et al.*, 2008; Borreani and Tabacco, 2010) suggests that the current baled silage making practices can be considered only partially satisfactory (McEniry *et al.*, 2011). In bale silages, more than 40% of the stored forage

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DM is within 120 mm of the film cover, and the reduced total thickness of the combined layers of stretch-film on the bale side, usually 70 µm (four layers) to 105 µm (six layers), could be expected to make individually wrapped bales more susceptible to oxygen ingress (Forristal and O'Kiely, 2005). Even small holes that can occur on farms, due to both mechanical and wildlife factors, can result in quantitative DM losses because of mold growth, especially in conserved forages with higher DM contents (McNamara *et al.*, 2001; Müller *et al.*, 2007). Air penetrating into the silage stimulates aerobic bacteria, yeasts and molds and causes aerobic deterioration (Borreani and Tabacco, 2008; O'Brien *et al.*, 2007). Moreover, under farm conditions, the improper mixing of different parts of the baled silage in the feed-mixer could enhance the final fungal and mycotoxin feed contamination. Farm surveys conducted in Ireland to establish the incidence of fungal growth on baled grass silage have shown that up to 90% of the examined bales had visible fungal growth (O'Brien *et al.*, 2008). Furthermore, Borreani and Tabacco (2010) observed, in a temperate environment, that the development of molds in the peripheral areas of a bale could involve more than 10% of the bale surface, when the conservation period was longer than five months. Therefore, to keep the molded surface as low as possible and to ensure good, stable bale silage conservation, air-tightness has to be maintained for extended conservation periods. A significant reduction in mold growth and an improvement in silage conservation quality are obtained when six or eight layers of film are applied, compared to four (Keller *et al.*, 1998; Müller, 2005). This is more evident when high DM forages are ensiled in wrapped bales and conserved for periods of more than 8 months (especially for alfalfa, *Medicago sativa* L., Borreani and Tabacco, 2008). More layers of stretch film assure a better airtight cover, but involve prohibitive increases in costs, in plastic usage and in environmental concerns, due to necessity of disposing of the additional plastic (Lingvall, 1995).

Furthermore, the cover can easily be damaged, especially for dry alfalfa, where stems can puncture the plastic film in the corners (shoulders) of the bale, and this leads to large DM and quality losses (Bisaglia *et al.*, 2011). As with all forms of silage, moist bales must be sealed rapidly to deplete the remaining $O_2$ and initiate fermentation. Sealing was originally performed manually by placing a large plastic bag over each bale (Savoie and Jofriet, 2003). Today, specialized machines (wrappers) provide a seal by applying a stretchable, thin, plastic film around the bale (Savoie and Jofriet, 2003). The wrapping method has not been changed since 1984, when the first bale wrapper model was introduced in Europe by the Norwegian company Kverneland-Underharg (Anonymous, 1995). Two main types of round bale wrapper are currently available: the rotating table and the rotating arm (Lingvall, 1995). Combined baler-wrapper units that can only wrap in the field have become common (Forristall and O'Kiely, 2005).

However, the stretch polyethylene wrapping system has shown some limits, with regards to sealing efficiency (Jacobsson *et al.*, 2002), concerning the high permeability to oxygen of stretch films (Borreani and Tabacco, 2008; 2010) and the non-uniform distribution of plastic films between the ends and the curved surface of the bale (Borreani *et al.*, 2007). These problems have lead to undesirable air exchanges over the conservation period, and it has been suggested that an increasing number of plastic film layers is required. For these reasons, great efforts have been made to reduce the possibility of damage to the plastic and of air ingress through the plastic cover during the conservation period.

## Bale silage fermentation

The wilting of forages, prior to wrapping them as baled silage, is an important part of the baled silage production system, since it reduces the number of bales per hectare, as well as the amount and cost of the stretch film used for wrapping. At a farm level, a greater DM content at baling than 35% is commonly found, and this increases the risk of molding and heating that are mainly related to difficulties in the exclusion of oxygen (Han *et al.*, 2006). A high DM content leads to weak fermentation, due to a lack of moisture for active fermentation, and to sugar consumption by aerobic microbes and plant activity to deplete the high amount of oxygen trapped in silages. Both the rate and the extent of silage fermentation are affected by the forage DM content at baling (Han *et al.*, 2014). A difference of around 0.5 pH units lower for chopped bunker silages than for wrapped bales, in relation to the DM content in alfalfa and Italian ryegrass (*Lolium multiflorum* Lam.) farm silages in northern Italy, is reported in Figure 1. The DM content at baling and the type of crop influence the fermentative profiles of the bales (Figure 2; Table 1). Commonly wrapped bales present lower lactic acid and volatile fatty acid contents than silages in bunker silos, due to the lack of release of soluble sugars by chopping (Muck and Shinners, 2001). Muck and Shinners (2001) reported that baleage does not ferment as much as chopped silage, and the DM should be 5 to 10 percentage units higher to prevent clostridial fermentation. The lactic acid content for a greater DM content than 50% is found, in most cases, to be below

20 g/kg DM. A low moisture content, a low lactic acid content and a high pH can result in mold covered baled silage (O'Brian *et al.*, 2007; Borreani and Tabacco, 2008), therefore preservation mainly depends on a low water activity and perfect anaerobic conditions rather than the silage acids, as is the case with more moist silages. Bales with a greater butyric acid content than 5 g/kg DM have been found in baleage with a DM content of up to 45% (Figure 3). Although fermentation in heavily wilted forage can be weak and the pH can be high, well-sealed baleage of alfalfa and perennial ryegrass has been shown to maintain a greater nutritive value than hay (Han *et al.*, 2004; Han *et al.*, 2006).

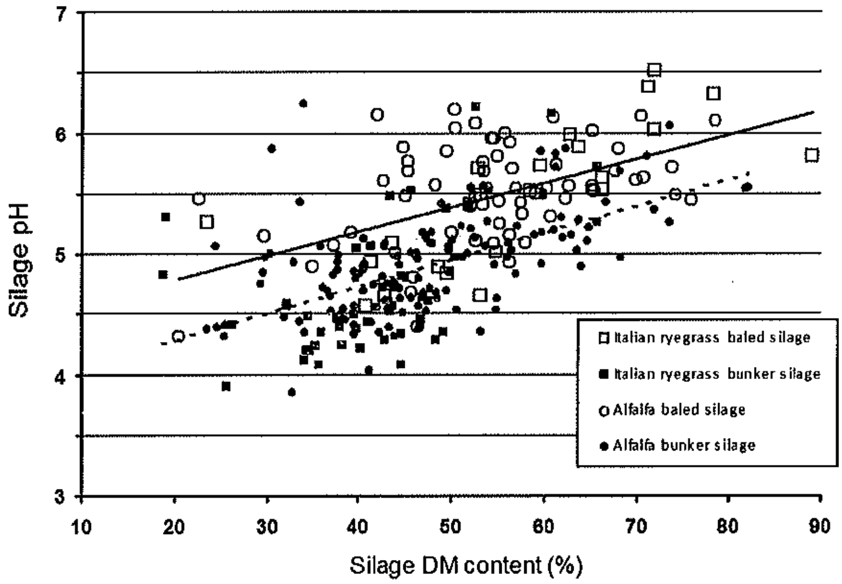


**Figure 1 -** Relationship between silage pH and DM content of alfalfa and Italian ryegrass silages conserved in bunker silos (dotted regression line) and in wrapped bales (continuous regression line) on farms in northern Italy.

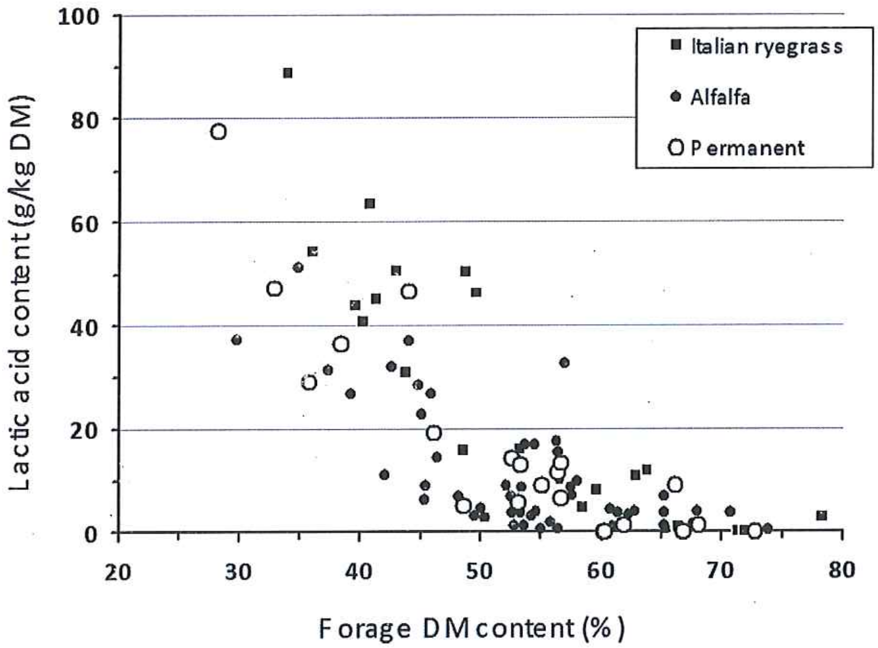


**Figure 2 -** Scatter plot of lactic acid versus DM content in well conserved wrapped bales of alfalfa, Italian ryegrass and permanent meadow on dairy farms in northern Italy.

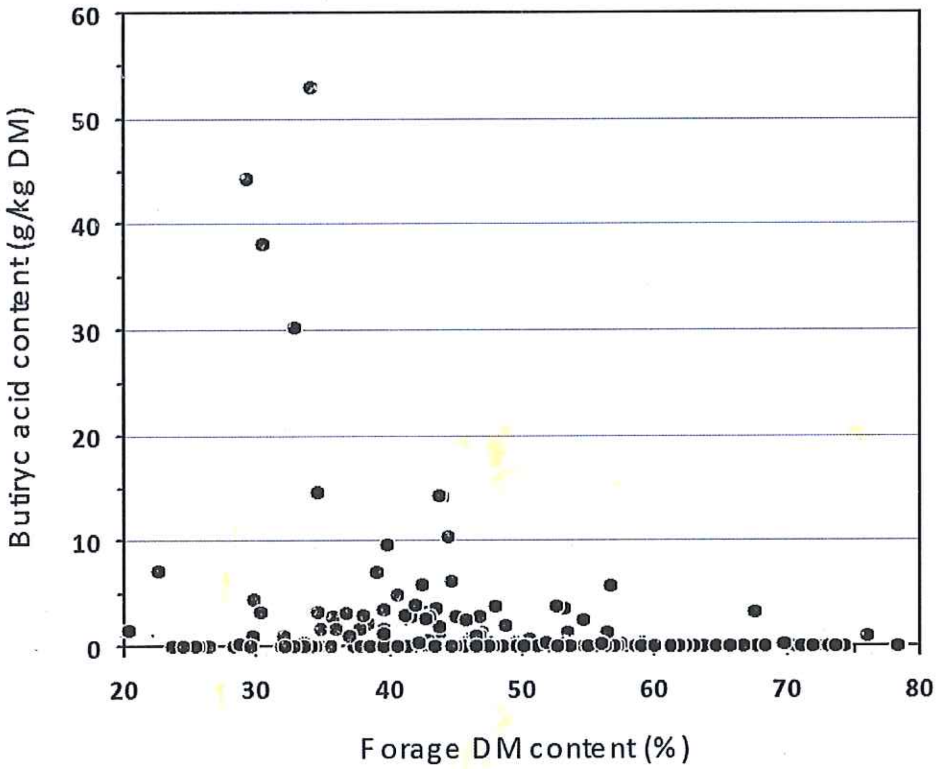


**Figure 3 -** Scatter plot of butyric acid versus DM content in conserved wrapped bales of alfalfa, Italian ryegrass and permanent meadow on dairy farms in northern Italy (n. = 299).

**Table 1 -** Effect of DM content and crop type on fermentative characteristics (g/kg DM or otherwise stated) of well conserved bale silages.

| Forages | DM content | pH | Lactic acid | Acetic acid | Butyric acid | Source |
|---|---|---|---|---|---|---|
| Alfalfa | 35 to 40% | 4.32-5.17 | 23.8-51.0 | 10.3-27.0 | < 0.01-1.9 | Borreani *et al.*, 2007 |
| | | 4.49-4.62 | 44.7-46.4 | 15.3-21.3 | 0.2-0.8 | Hancock and Collins, 2006 |
| | 40 – 60% | 5.27-6.08 | 9.9-37.0 | 3.5-16.9 | < 0.01-0.6 | Borreani and Tabacco, 2008 |
| | | 4.80-4.93 | 13.3-19.6 | 3.5-6.6 | 0.4-0.8 | Hancock and Collins, 2006 |
| | >60% | 5.31-6.14 | 2.1-6.8 | 1.2-7.8 | < 0.01-0.3 | Borreani and Tabacco, 2010 |
| Italian ryegrass | 30 to 40% | 4.21-4.63 | 22.2-90.1 | 9.9-31.6 | < 0.01-3.5 | Bisaglia *et al.*, 2011 |
| | 40 – 60% | 4.57-5.73 | 12.6-63.2 | 1.4-17.1 | < 0.01-3.5 | Borreani and Tabacco, unpublished |
| | >60% | 5.52-6.51 | < 0.01-11.8 | < 0.01-6.1 | < 0.01-0.1 | Borreani and Tabacco, unpublished |
| Permanent meadow | 30 to 40% | 4.11-4.58 | 28.8-79.4 | 8.4-25.1 | < 0.01-3.2 | Borreani and Tabacco, unpublished |
| | 40 – 60% | 4.66-5.72 | 2.4-46.4 | < 0.01-12.0 | < 0.01-5.7 | Borreani and Tabacco, unpublished |
| | >60% | 5.96-6.32 | 1.4-8.9 | < 0.01-3.4 | < 0.01 | Tabacco *et al.*, 2013; Muller *et al.*, 2011 |
| PM with timothy* | 30 to 40% | 4.65 | 38.3 | 11.3 | 0.8 | Muller *et al.*, 2007 |
| | 40 – 60% | 5.55 | 2.0 | 2.0 | < 0.01 | Muller *et al.*, 2007 |
| | >60% | 5.72 | 0.4 | 0.7 | < 0.01 | Muller *et al.*, 2007 |

* PM = permanent meadow.

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# New Technical Solutions To Improve Bale Silage Quality

The technical solutions that have recently appeared on the market involve the following aspects: improved bale densities, especially for high DM content silages; increased uniformity of the plastic distribution over the bale surface; reduced plastic permeability to oxygen. The rapid development in wrapping bale technology has led to a great improvement in the ensiling process, and this has been achieved by increasing bale densities with round balers equipped with a crop-cutter (Shinners, 2003; Borreani and Tabàcco, 2006), reducing the working times with combined baler-wrapper machines (Münster, 2001), and improving the uniformity of the plastic distribution on the bale surface with a new-concept 3D wrapping system (Borreani *et al.*, 2007) or round balers equipped with film-tying attachments to replace the standard net-tying system with a film tying system, in order to improve the airtightness of the coverage on the bale curved surface (Bisaglia *et al.*, 2007).

## *Improving bale density*

Since the 2000's, forage crops formed in round bales for silages generally have undergone little if any size reduction during harvesting (Shinners, 2003). Herbage is rolled during baling, but this does not give the bale a high density and it makes oxygen exclusion more difficult. Silage compaction has been improved by reducing the chop-length of herbage, with denser bales resulting in lower handling and transport costs (Ohlsson, 1998).

Round balers with a cutting system behind the pickup are available on the market and could provide the following advantages: density increases of up to 15%, with subsequent improvements in baler productivity and silage quality (Borreani and Tabacco, 2006), and bales are more readily processed by TMR mixer-feeders (Shinners, 2003). The technique of cutting the herbage into shorter lengths on entry to the bale chamber could facilitate the release of plant sugars, and thus provide an aid to obtaining a better bale density (Shinners, 2003). Borreani and Tabacco (2006) observed, on alfalfa round bales, that the chopping system increased the percentage of stems that were shorter than 10 cm, from 14 to 38% on a DM basis, compared to unchopped bales. This reduction in particle size resulted in a reduction of the power requirements and loading times during feed mixer operations (Bisaglia *et al.*, 2002). Increases in big bale weight, due to the chopping device, have been reported in several researches (Ohlsson, 1998; Bisaglia *et al.*, 2002; Borreani and Tabacco, 2006) and are summarized in Table 2.

Other advantages are that the dispersion of additives within a bale is likely to be improved in bales made from precut forage (Lingvall, 1995).

**Table 2** - Effect of cutting device applied to baler in increasing bale weight.

| Forages | Baler | DM content (%) | Bale weight increase due to cutting device | Source |
|---|---|---|---|---|
| Alfalfa | fixed chamber | 35.0 | 2.5 | Borreani and Tabacco, 2006 |
| | fixed chamber | 60.5 | 4.7 | Borreani and Tabacco, 2006 |
| | fixed chamber | 50.7 | 7.8 | Bisaglia *et al.* (2001) |
| | variable-chamber | 50.7 | 14.3 | Bisaglia *et al.* (2001) |
| | variable-chamber | 43.1 | 3.0 | Borreani and Tabacco, 2002 |
| Italian ryegrass | fixed chamber | 33.6 | 3.3 | Bisaglia *et al.*, 2001 |
| | variable-chamber | 33.6 | 8.7 | Bisaglia *et al.*, 2001 |
| Permanent meadow | variable-chamber | 47.3 | 8.4 | Borreani and Tabacco, 1999 unpublished data |
| Barley | variable-chamber | 32.6-42.7 | 7 to 9% | Ohlsson, 1998 |

### *Increasing the uniformity of the plastic distribution*

Traditionally, four layers of polythene are applied in two subsequent and complete rotations of a bale, with an overlap of 50% between layers. A significant reduction in mold growth and improvement in silage conservation quality can be obtained when six or eight layers of film are applied rather than four (Keller *et al.*, 1998). Increasing the layers with a conventional wrapping system causes a non-uniform distribution of the plastic film between the end and the side of the bale, with a waste of plastic film, due to the higher proportion of plastic distributed on the flat ends (Figure 4 – conventional wrapper). To increase the uniformity of plastic distribution, two different solutions have recently appeared on the market: the selective 3D wrapper and round-balers equipped with a tying system to secure large round bales with polyethylene tying-film in the baler chamber.

The commercial availability of a new concept of selective wrapper (3D), alone or mounted onto the rear of a baler, offers an improved film application method for round bale silage. It was first proposed as a prototype by the Vicon-Kverneland Group (Bisaglia *et al.*, 2003). The new-concept selective 3D wrapper is based on a biaxial rotation of film applicators (Figure 5), and it is of great interest because it reduces the amount of plastic used per bale, while improving the uniformity of the plastic distribution on the surface and increasing the number of layers in the areas that are most at risk to damage (Borreani *et al.*, 2007). Borreani *et al.* (2007) reported that the uniformity of the plastic distribution over the bale is increased, in comparison to a conventional wrapper, and this system allows at least seven layers to be applied over the whole bale surface with less plastic than the amount utilized by a conventional wrapper to wrap a bale in six layers (a 3D wrapper utilizes from 0.862 to 0.976 kg of plastic per bale vs. a conventional wrapper which consumes 1.013 kg of plastic per bale for 6 layers) (Figure 4). In a conventional wrapper bale, which is nominally wrapped with four layers of plastic film, the flat ends have as many as 16-20 layers in the center, a number which gradually decrease to four layers at the outer edge and on the curved surface. The 3D wrapping method has improved the bale silage technique by reducing the amount of plastic on the flat ends, without lowering the fermentation and conservation quality of silages. This improvement in the distribution of the plastic over the bale surface reduces mold development, and protects the bale edges from the damage of alfalfa stems (Borreani *et al.*, 2007). The new-concept wrapper produces well-shaped bales that do not loose their shape during storage.

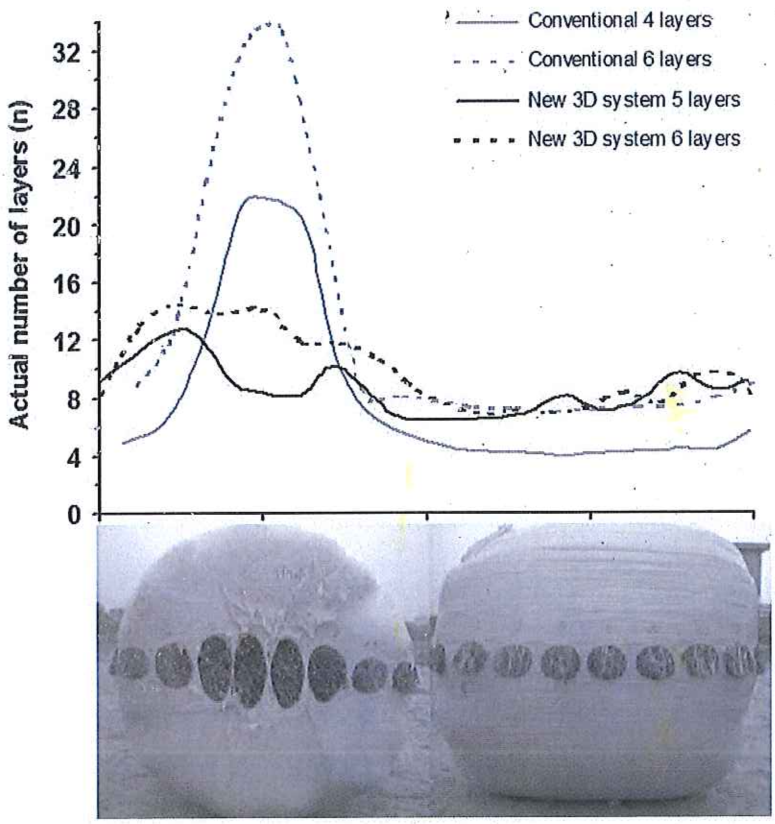


**Figure 4 -** Number of layers at the end and at the side of bales for the two wrapping systems and two different layer settings. The numbers on the horizontal axis are the distances (mm) around the median outer edge of the bale, starting from a corner (Adapted from Borreani *et al.*, 2007).

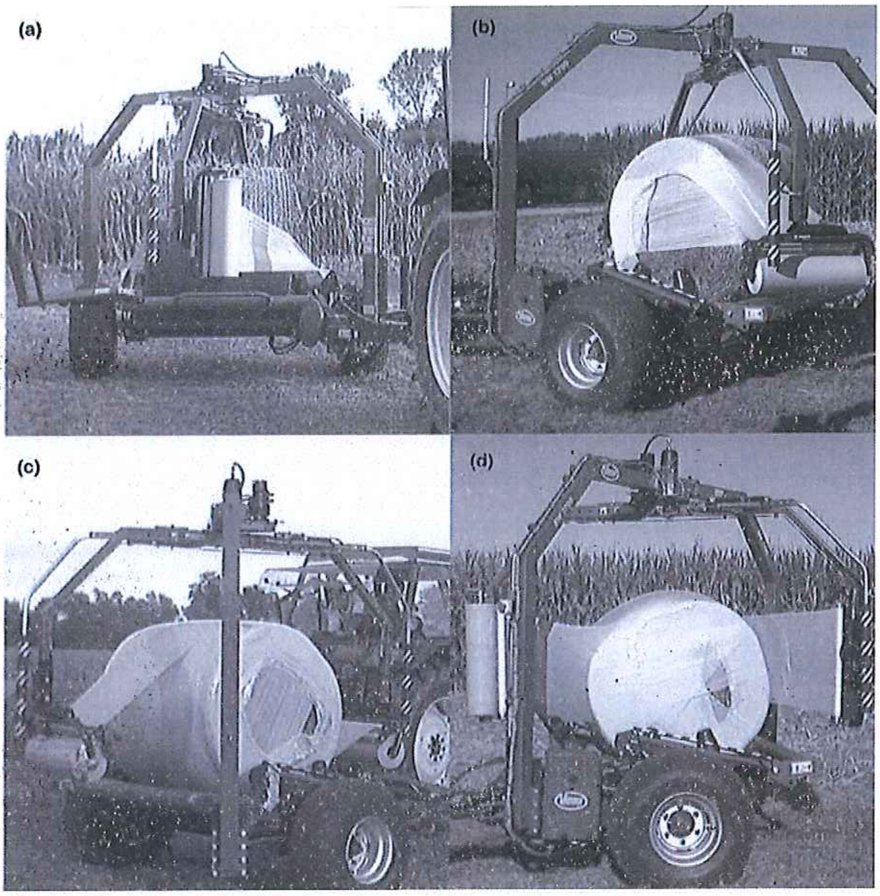


**Figure 5 -** The working sequence of the 3D prototype wrapper (Vicon BW 1700 3D): pre-stretchers in a vertical position beginning to wrap (a), pre-stretchers in a horizontal position wrapping the edge of the bale (b), pre-stretchers in a horizontal position wrapping the central part of the side (c) and pre-stretchers, reverted back to a vertical position, finishing the bale with 2 layers (d) (Adapted from Borreani *et al.*, 2007).

Some new-generation balers that have recently come onto the market are equipped with tying systems that allow a bale to be secured in the press chamber using twine, net, or polyethylene film. Bisaglia *et al.* (2011) investigated the possibility of replacing the standard net used to secure bales with polyethylene film (Figure 6). They found that film-tying reduced the mold-covered surface on the curved side of the bales, and that it could represent an interesting alternative to net-tying when preparing round bales for silage. The same authors, concluding their work, pointed out the need to obtain a better bale-edge covering to further reduce the possibility of mold growth over the conservation period.

As a result of their research, a film tying system was developed to better cover the bale edges. Tabacco *et al.* (2013) studied the possibility of reducing mold growth on the surface of low-moisture baled silage of grass-legume mixtures for a long conservation period (8 months), without increasing plastic costs, by replacing polyethylene net with polyethylene tying-film to secure large round bales in the baler chamber. The high DM content of the silages restricted fermentation and resulted in low concentrations of acids, with pH values in the inner part of the bale ranging from 5.41 to 5.70. The tying film was well distributed over the curved side and over the edges of the bales (Figure 7), and did not show any signs of damage due to mechanical operations (ejection, handling, wrapping). The use of tying film, compared to net, led to a reduction in the number of holes and an improvement in the anaerobic status of the baled silage, even with just four layers of stretch-film, and resulted in a decrease in mold counts and visible mold growth over the bale surface (Table 3). In conclusion, they reported that with similar costs for plastic and the same amount of plastic used to secure the bale with net and wrap it in four layers of stretch-film, it is possible, using a tying film of 16 μm in the baler chamber, to obtain more than six effective layers of plastic on the curved side and on the edges of the bale, and therefore to reduce the risk of cover puncturing and the incidence of mold growth over the bale surface to a similar level to that of baled silage wrapped in six layers of polyethylene and secured with net. Furthermore, increasing the number of stretch-film wraps from four to six, while using a polyethylene tying-film, not only increased the actual numbers of layers on the round side and edges of the bale, but also reduced the mold growth over the bale surface of high wilted silage to a lower value than 1%, without increasing the total plastic usage and costs, compared with bales secured with polyethylene net.

**Figure 6** - Bale tied with film after ejection from the baler chamber waiting to be wrapped.

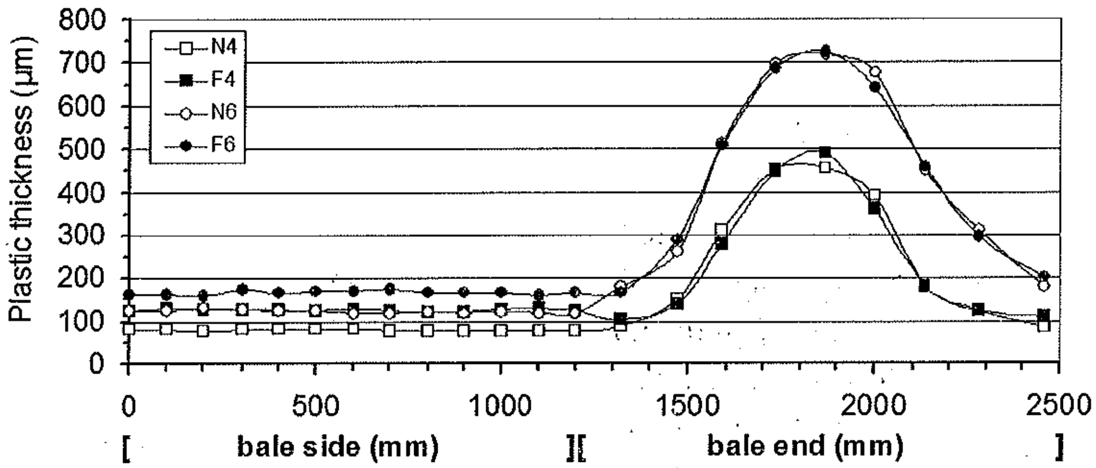


**Figure 7 -** Total plastic thickness at the side and end of the bale for the tying film compared to the net tying system and two different layer settings (four vs. six). The numbers on the horizontal axis are the distances (mm) around the median outer edge of the bale. N, tying net; F, tying film; 4, four layers of stretch-wrap; 6, six layers of stretch-wrap (from Tabacco *et al.*, 2013).

**Table 3 -** Bale weight, bale density, plastic consumption, plastic thickness on the curved side of the bale, plastic damage, surface covered by mold, DM losses, and costs of plastic in relation to the tying method and the number of plastic layers applied (from Tabacco *et al.*, 2013).

| Items | Tying Method | | | |
|---|---|---|---|---|
| | Net-tying | | Film-tying | |
| | 4 Layers | 6 Layers | 4 Layers | 6 Layers |
| Net/film per bale for tying (g) | 216 | 209 | 260 | 271 |
| Stretch-film wrap per bale (g) | 901 | 1275 | 901 | 1256 |
| Total plastic per bale (g) | 1117 | 1484 | 1161 | 1527 |
| Thickness of stretch-film wrap (µm)[c] | 79 | 121 | 81 | 119 |
| Thickness of tying film (µm)† | - | - | 43 | 46 |
| Micro-holes in the plastic cover (n) | 14 | 5 | 7 | 3 |
| Surface covered by mold (%) | 25.3 | 2.6 | 3.3 | 0.8 |
| DM losses (g/kg DM) | 56 | 30 | 29 | 28 |
| Cost of the tying film/net (€/bale) | 0.81 | 0.78 | 0.71 | 0.75 |
| Cost of the stretch-film wrap (€/bale) | 2.92 | 4.12 | 2.91 | 4.06 |
| Plastic cost per bale (€) | 3.72 | 4.91 | 3.63 | 4.81 |
| Plastic cost per tonne of harvested DM (€) | 10.97 | 14.00 | 9.58 | 13.30 |

## *Oxygen barrier films to wrap bale silages*

Borreani and Tabacco (2010) observed, in a temperate environment, that the development of molds in the peripheral areas of the bale could involve more than 10% of the bale surface, when the conservation period is longer than 5 months. Even though the baled silage system is based on a well-established procedure, the fact that the incidence of mold spoilage can be relatively high (O'Brien *et al.*, 2008; Borreani and Tabacco, 2010) suggests that the current baled silage making practices should be considered only partially satisfactory (McEniry *et al.*, 2011). Although the usual recommendation to farmers is to use six nominal layers of stretch film to provide a valuable safety margin, many authors (Lingvall, 1995; Keller *et al.*, 1998; Paillat and Gaillard, 2001) have demonstrated that, when using commercial PE stretch films, the amount of oxygen that diffuses into the bale during storage, and consequently the amount of visible molding that occurs, can only be reduced by applying more film layers, but, as previously stated, this requires longer wrapping times, as well as an increase in costs and environmental concerns. Improving the oxygen impermeability of stretch film has thus been identified as one of the most effective ways of obtaining significant improvements in the conservation quality of baled silage (Borreani and Tabacco, 2008, 2017). New plastic manufacturing technologies, coupled with new low oxygen permeability polymers that can be coextruded with PE, offer the possibility of producing multilayer stretch films for the wrapping of bale silages at costs that are competitive with those of the conventionally used PE on farms (Borreani and Tabacco, 2005). Furthermore, these new films could solve the problems that have restricted the application of wrapping technology to silage with a higher DM content than 60% (Borreani and Tabacco, 2008, Borreani *et al.*, 2009). Polyethylene (PE) has been used for many years for the industrial production of plastic films for wrapping bales because of its suitable mechanical characteristics and low costs. Most plastic films for stretch-wrap silage production are made of coextruded, linear low-density polyethylene, and are 25 μm thick before being stretched 50% or more during application. The high $O_2$ permeability of PE films seems to be one of the main drawbacks of wrapped silage, especially for conservation periods longer than six months (Borreani and Tabacco, 2008).

A new oxygen barrier stretch film, with an 18-fold lower oxygen permeability than that of the PE stretch film commonly used on farms, has recently become available in Italy. This new material may solve the problems that have restricted the application of the wrapping technology to extremely wilted alfalfa silage, without increasing the amount of plastic applied (Borreani and Tabacco, 2008, Borreani *et al.*, 2009). Furthermore, Borreani and Tabacco (2008) showed the possibility of using four layers of an oxygen barrier film instead of six layers of a PE film, without increasing the risk of mold damage on baled alfalfa silage. Paillat and Gaillard (2001) reported that stretching to

60% reduced the thickness from 25 to 19 μm, accelerated film wear, and on average decreased the service life of a film by 48%. Furthermore, Hancock and Collins (2006) reported that the oxygen permeability of a single layer of PE film stretched to 150% of its original length increased to values ranging from 7750 to 9810 $cm^3/m^2/d$, according to the manufacturing process.

Since the oxygen impermeability of stretch film seems to have a great effect on reducing the spoilage of bale silage and DM losses, it is crucial to define the level of oxygen impermeability of the stretch film that could improve the conservation quality of wrapped bales, without increasing plastic consumption. Some polymers that are different from PE, such as polyamides (PA) and ethylene-vinyl alcohol (EVOH), offer excellent barrier properties to oxygen, combined with good mechanical characteristics (puncture resistance and stretch properties), and they are suitable for blown co-extrusion with PE (Borreani and Tabacco, 2017). These polymers are also characterized by the absence of chlorine in their molecules, thus reducing the risk of dioxin production if they are burned. EVOH combines the excellent barrier properties of polyvinyl alcohol to oxygen with those of PE against water. The second group of polymers is PA, which is also known as nylon, and it was first produced in 1935 as a synthetic replacement for natural silk. PA has a good thermal stability, but an oxygen permeability that is about 30 times greater than that of EVOH. The oxygen permeabilities of these polymers, for a 1 μm thickness film under standard conditions (23°C, 1 bar, and 65% RH), are 1380 for PA and 38 for EVOH, versus 178,000 $cm^3\ m^{-2}\ d^{-1}$ for low-density PE. Another important factor that is often neglected is the influence of temperature on the permeability coefficient, which increases exponentially with temperature. This leads to a 7.4-fold increase in permeability when a film heats to 70°C in the sun (Daponte, 1994). Daponte (1992) also reported that the oxygen permeabilities of low quality to high quality PE silage films are close to each other in the thickness range because a nearly linear relationship exists between permeability and film thickness.

A first attempt at using co-extruded oxygen barrier (OB) stretch-wrap films with baled silage was described in detail by Borreani and Tabacco (2005 and 2008). This first generation of OB stretch-wrap film was developed by means of the co-extrusion of LDPE with PA. The results showed an evident effect of the film type and number of layers on the percentage of bale surface covered by mold, with lower values than 15% in the bales wrapped with at least 4 layers of OB film conserved for longer periods than eight months. Storage DM losses were also affected by the type of film that was used and by the number of layers applied, with consistently lower values in OB silages for at least four layers of film (Borreani and Tabacco, 2008). It was concluded that the new stretch film could be used to conserve silage for more than eight months, without any decrease in the conservation quality or prohibitive increases in costs and plastic usage.

Further improvements in oxygen impermeability for films used to cover bunker silage were obtained by co-extruding a thicker layer than 2 μm of a special grade of EVOH between two or more layers of PE (Borreani *et al.*, 2009). The oxygen impermeability of the new high oxygen barrier (HOB) film was improved by about 21- and 374- fold, compared to that of first generation of OB and standard PE films, although it maintained similar mechanical properties to those of the best performing PE stretch film (Table 4).

**Table 4 -** Characteristics of three stretch films (25 μm thick) with different oxygen impermeability. The measurements were conducted on new film before stretching (data from Borreani and Tabacco, 2010).

| Characteristics | Plastic film | | |
|---|---|---|---|
| | PE | OB | HOB |
| Oxygen permeability at 23°C† | 7120* | 408 | 19 |
| Oxygen permeability at 50°C† | 21360* | 2062 | 45 |
| Puncture resistance to probe penetration (mm) | 20.8 | 12.4 | 16.7 |
| Tensile strength at break, MD (MPa) | 62.0 | 34.1 | 34.5 |
| Tensile strength at break, TD (MPa) | 37.6 | 23.2 | 22.9 |
| Elongation at break, MD (%) | 534 | 425 | 716 |
| Elongation at break, TD (%) | 1015 | 497 | 942 |

HOB, high barrier film; OB, medium barrier film; MD, machine direction; PE, standard polyethylene film; TD, transverse direction. † ($cm^3/m^2/24$ h at 0.1 MPa and 65% RH); * From the barrier database.

When tested in research trials performed at a farm scale, the HOB stretch films with improved oxygen impermeability were effective in reducing the DM losses during conservation to values of around 2% for alfalfa baled silage with a DM content ranging from 55 to 65% (Figure 8).

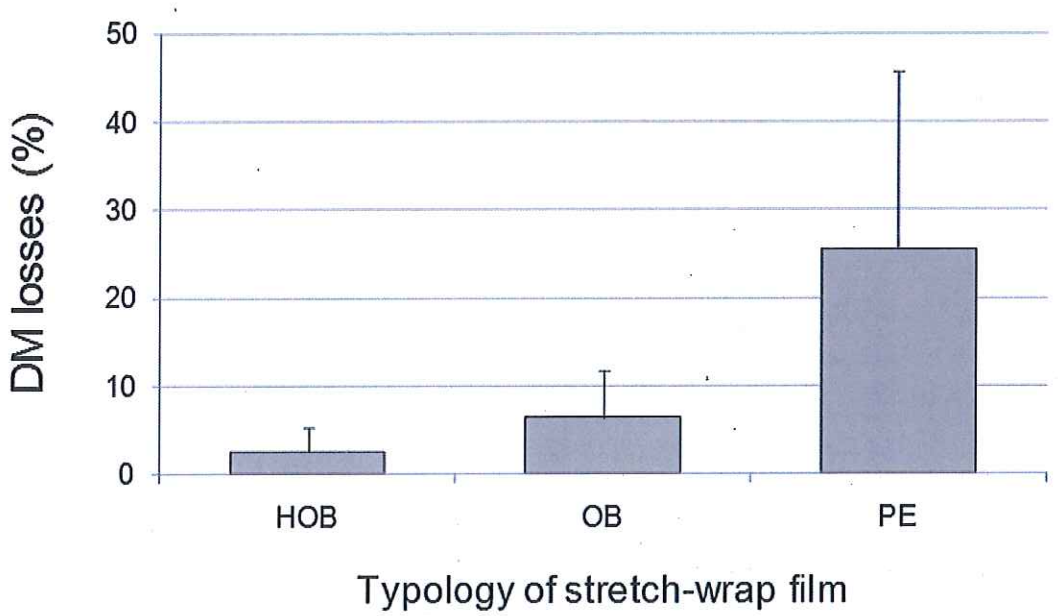


**Figure 8 -** DM losses in relation to oxygen impermeability of stretch films in alfalfa baled silages after 420 d of conservation (average of three trials in Northern Italy). HOB, high barrier film; OB, medium barrier film; PE, standard polyethylene film (Adapted from Borreani and Tabacco, 2010).

Other authors have reported DM losses of 6% (Hancock and Collins, 2006), or of 7% of the total harvested DM (Shinners *et al.*, 2009b; Borreani and Tabacco, 2008) for alfalfa silage baled at similar DM contents and wrapped with standard PE stretch films. The improved oxygen impermeability has also had a remarkable influence on the evolution of the surface covered by mold: the higher the barrier properties of the plastic film utilized to wrap the bales are, the greater the reduction in mold growth on the bale surface over the conservation period (Figure 9). Owing to the possibility of using less plastic and a lower number of layers on the bale surface, the next research steps shall be focused on establishing bale management tips which could provide greater protection from mechanical damage and reduce the risk of plastic puncturing during handling and conservation (which currently can only be provided by increasing the amount of plastic applied).

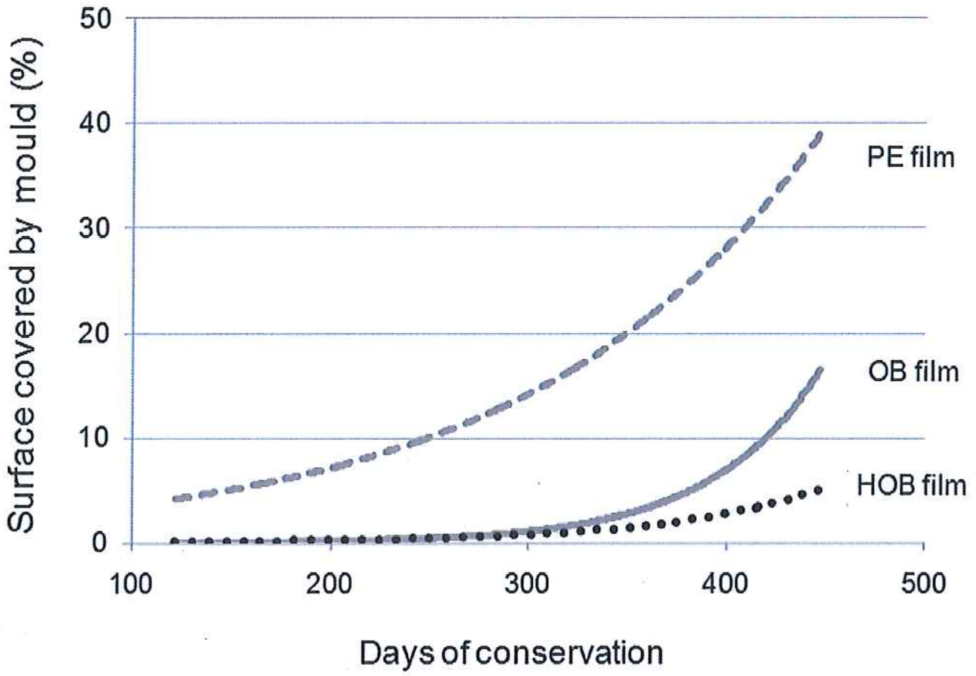


**Figure 9 -** Surface covered by mold in relation to days of conservation in baled alfalfa silage wrapped with stretch film with different oxygen impermeability. HOB, high barrier film; OB, medium barrier film; PE, standard polyethylene film (Adapted from Borreani and Tabacco, 2010).

## *Plastic bale damage*

Bales are usually wrapped in the field immediately after baling and before being transported to the storage site and invariably stored outdoors (McNamara *et al.*, 2001). If the integrity of a stretch film is damaged during storage, the subsequent ingress of oxygen will permit the growth of filamentous fungi and other micro-organisms, thus resulting in extensive quantitative and qualitative losses (McNamara *et al.*, 2001; Kawamoto *et al.*, 2012). The plastic stretch-film surrounding baled silage is prone to damage during storage, prior to being fed to livestock, by many vertebrates. Damage by birds (McNamara *et al.*, 2002) and by rats (Kawamoto *et al.*, 2012) has been reported to be the most frequent on farms, while that caused by cats, dogs and other farm livestock is comparatively limited (McNamara *et al.*, 2002). Direct physical barriers to bird access, as opposed to scaring devices, such as the use of nets securely positioned 1 m above and beside the bales, appear to be the most reliable way of preventing damage (McNamara *et al.*, 2002). Whole cereal baled silages result to be particularly attractive to rats, which could easily damage bales stored under a masking situation (Kawamoto *et al.*, 2012). It is suggested that creating open spaces between the bales and not covering bales with plastic sheets reduces the number of hiding places that are available for rats, thereby decreasing their potential damage.

# New possibilities of ensiling fine chopped material in wrapped bales

New machines that integrate a baler and a wrapper together are now available on the market, and they increase productivity and reduce operation costs compared to the use of two separate machines. In recent years, new combined baler-wrapper machines have been developed with the aim of baling fine chopped material or fine-particle biomass and wrapping them with stretch plastic. Many of these new machines have adopted some or all of the technical solutions described above, such as film tying in the compression chamber and two 3D film dispensers to speed up the wrapping operation and increase the homogeneity of the plastic distribution over the bale.

The first attempt to assemble a baler with its own wrapping device were made in Finland (Anonymous, 1992), while the first machine that was able to bale fine chopped material was developed in Norway (Anonymous, 1990), and it was designed to be top-filled by a forage chopper (Figure 10).

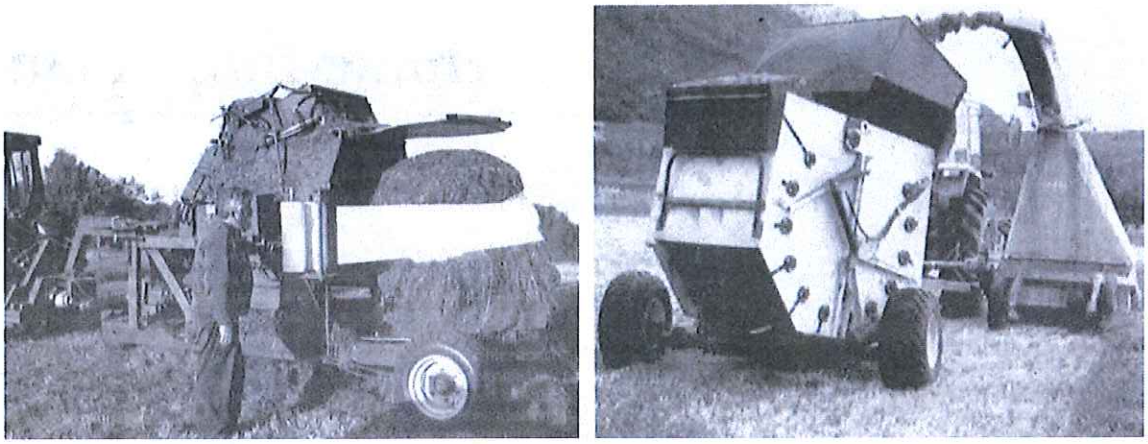

**Figure 10 -** The first combined baler-wrapping machine developed in Finland and the first baler used to ensile fine chopped material, which was developed in Norway (from Anonymous, 1990, 1992).

Shito *et al.* (2006) reviewed the development of roll balers for chopped materials made at the beginning of the current century. Weinberg *et al.* (2011) described and presented the results of a commercial established process that is based on the production of dense bales of silage under high pressure, followed by packing and wrapping with 8 to 9 layers of polyethylene stretch film. This technology has been successfully used for the preservation of high-moisture by-products stored with dry feeds (Miron *et al.*, 2012; Shaani *et al.*, 2015), or as completely finished total mixed rations (TMR) for lactating dairy cows (Wang *et al.*, 2010; Weinberg *et al.*, 2011). Ensiling TMR is becoming a wide-spread practice, and the advantages attributed to it include the supply of homogeneous feed over time to the animals, labor savings during preparation and the opportunity to include otherwise perishable moist by-products (Weinberg *et al.*, 2011; Shaani *et al.*, 2015). Weinberg *et al.* (2011), Miron *et al.* (2012) and Shaani *et al.* (2015) indicated that the DM density of a bale was above 400 kg/m$^3$, which is more than twice the DM density of silage in a bunker silo (Savoie and Jofriet, 2003), a fermentation process takes place during storage even for already ensiled material, and the forage quality can be maintained outdoors for a long period of time, even under hot summer conditions. Furthermore, the preserved TMR had improved aerobic stability, compared with that of the fresh TMR.

As mentioned above, forage crops conserved as silage in round bales undergo a slight reduction in particle size during harvest (Muck, 2006), are baled at a higher DM concentration, are stored at a lower bulk density, and are less fermented than silages stored in bunker silos (Weinberg *et al.*, 2011). In the last few years, stationary compactor machines have been developed to suitably conserve, apart from finished TMR, fine chopped forage or ground grain that were previously only conserved in stack silos, thus allowing them to be stored until needed and to be transported like any other commodity. Many chopped forages, such as whole corn silage, whole ear corn silage and whole crop soybean silage, could be profitably preserved in wrapped bales as feeds for lactating cows on small-medium sized farms, as could fine chopped corn stover, rice straw and other lignocellulosic wastes, as ensiled biomass that could be used to produce bioenergy and biofuels (Borreani G. and Tabacco E., University of Turin, pers. com., 2017; Anonymous, 2017).

## Summary

The technical and research innovations developed over the last few decades in the field of wrapped bales provide an opportunity to successfully plan farm silage making, while maximizing silage quality and minimizing losses. The reported new technical solutions will improve the feasibility of producing high DM content baleage and of maintaining the nutritional and microbial quality of the forage, while reducing the cost per tonne of stored DM. The improvement in the uniformity of baled silage, in terms of nutritional and hygienic quality, is a priority to make this relatively new technique successful, a technique, which, when used properly, could increase the technical efficiency and economic sustainability of dairy production systems.

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