NRAES–5

Silage and Hay Preservation

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COOPERATIVE EXTENSION NRAES–5

Silage and Hay Preservation

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Key to Abbreviations

Acid Detergent Fiber: Cellulose plus lignin; high ADF correlates with low digestibility and increases as DM is lost.	**ADF**
Acid Detergent Insoluble Protein: Bound-nitrogen compounds unavailable for digestion, expressed as a protein equivalent (nitrogen × 6.25). Heating in the silo or in the barn increases ADIP.	**ADIP**
Crude Protein: Total nitrogen expressed as a protein equivalent (total nitrogen × 6.25). Loss of leaves decreases CP.	**CP**
Dry Matter: Compounds in forage, excluding water.	**DM**
Lactic Acid Bacteria: Beneficial bacteria that ferment silage.	**LAB**
Neutral Detergent Fiber: Hemicellulose plus cellulose plus lignin; high NDF correlates with low dry matter intake and increases as DM is lost.	**NDF**
Net Energy for Lactation: The energy content of the forage available for production, estimated from ADF.	**NE_L**
Soluble Protein: That portion of the crude protein which is readily available for microbial synthesis in the rumen; if large increases in SP occur in the silage, animal digestion can be adversely affected.	**SP**
Theoretical Length of Cut: Chop length calculated from the distance forage travels between successive knife cuts in the chopper.	**TLC**
Total Pan Evaporation: mm of water that would evaporate from an open pan while forage dries to baling moisture.	**TPE**

Introduction

Forage crops—legumes, grasses, and corn silage—form the basis of the nutritional programs on dairy, sheep, and beef farms in the Northeast. About two-thirds of the arable cropland in the Northeast is devoted to forage production. The majority of this forage is preserved as silage or hay.

From the moment the crop is cut until it is delivered to the animal, biological processes take place that decrease the quantity and nutritional quality of the feed. The goal in preservation is to conserve the digestible fiber, protein, and energy in the forage, and to maintain the protein in a form that can be efficiently utilized by the ruminant. This involves restricting the actions of bacteria, yeasts, molds, and plant enzymes, as well as browning reactions. Improved preservation results in more feedable forage and better feed utilization by the animal.

Hay Versus Silage Preservation

Hay-making and silage-making differ in how moisture content is employed as a strategy in preservation. Fresh forage contains about 80% moisture—4 lb of water for every 5 lb of forage. Soluble sugars and proteins are dissolved in the forage liquid, and this "juice" provides an ideal medium for the growth of yeasts, molds, and bacteria, and for rapid activity of plant enzymes. When forage is dried before harvest, the water in the forage evaporates, resulting in a higher concentration of solutes in the liquid. In this concentrated juice, cell growth and enzyme activity are restricted.

Figure 1 illustrates the effect of forage moisture content on various microorganisms and processes in forage. Yeasts and molds are microorganisms that degrade forage in the presence of oxygen. Lactic acid bacteria (LAB) and clostridia bacteria grow without oxygen. Plant proteases are enzymes which solubilize plant proteins. Browning is a chemical reaction associated with high temperatures. *The fundamental strategy in the preservation of forage as hay is to prohibit all of these processes by drying the forage to below 20% moisture content.*

Above 40% moisture content, these processes are active, and a different preservation strategy is needed. In silage-making, the forage is stored in oxygen-free (anaerobic) conditions which stimulate growth of lactic acid bacteria and prevent growth of molds and many yeasts. Bacterial growth without oxygen is called fermentation. The lactic acid bacteria use plant sugars to produce organic acids, lowering the pH from 6.0 to 3.8–4.5 in corn silage and to 4.0–5.0 in haycrop silage. Low pH means high acidity. In a low pH silage, cell growth and enzyme activity are restricted. *The fundamental strategy in the preservation of forage as silage is to exclude oxygen from the forage mass and to reduce the pH rapidly through bacterial fermentation.*

In the range of 20%–40% moisture content, neither strategy is effective in preserving forage. Figure 1 shows that browning reactions are at the highest level between 15% and 40% moisture content; these browning reactions produce heat and may cause hay and silage fires.

Important Issues in Silage and Hay Preservation

Losses

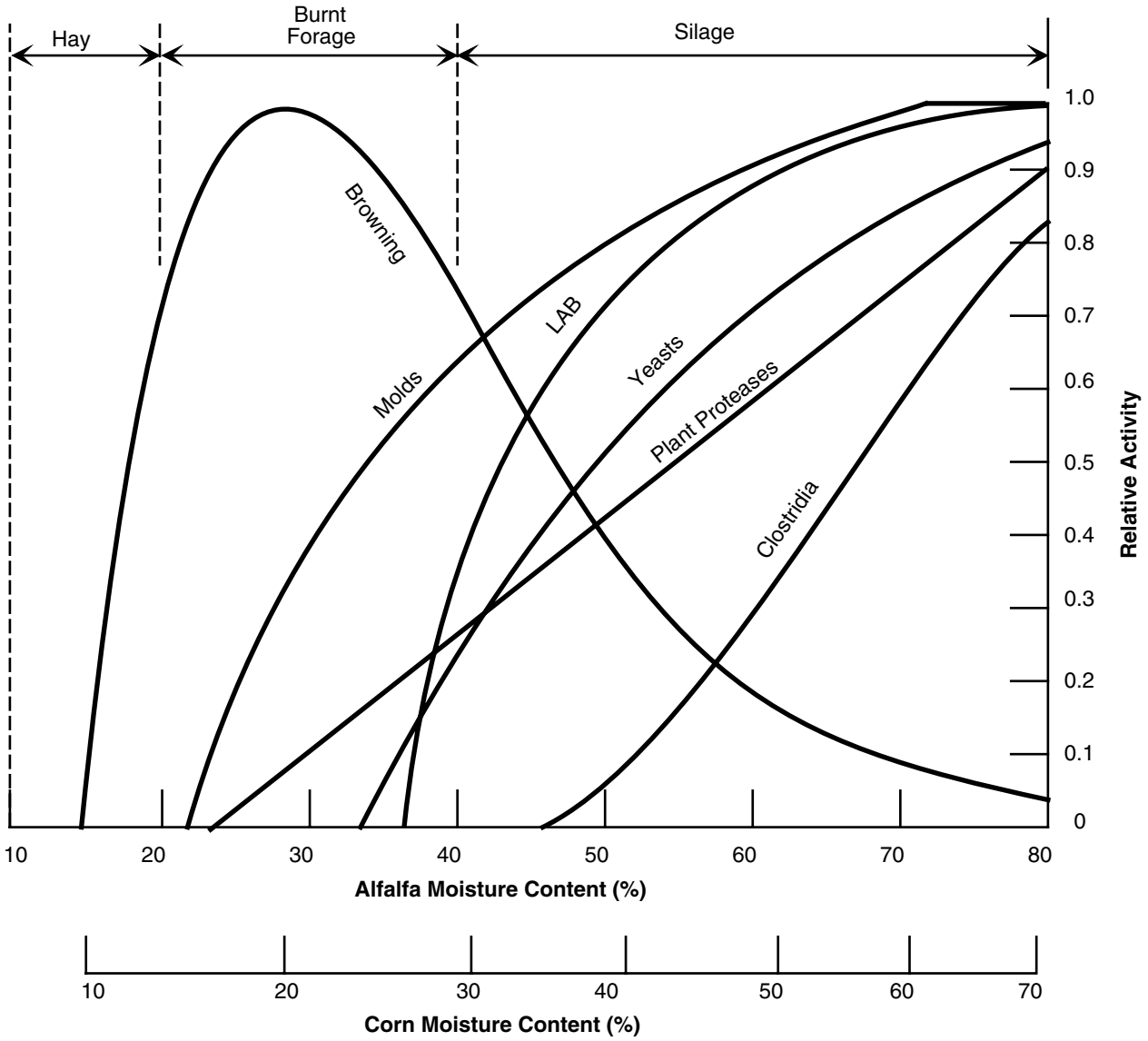
Each step in the preservation process (mowing, raking, chopping, baling, storing, unloading) causes a loss of forage DM. Some losses result from mechanical action; others are biologically based. Total losses from cutting to feeding are typically 20%–30% of DM.

Figure 2 illustrates the sum of these losses over a range of moisture content at harvest. DM losses in hay and silage systems total 15%–30%. In hay-making, most of the losses result from mechanical handling and weather damage in the field. In silage-making, most losses occur during storage and feeding out.

Quality Changes

Most of the DM lost from forage during harvest and storage has high nutritional value. More leaves than stems are lost during hay-making, and most protein- and energy-rich nutrients are concentrated in the leaves.

Figure 1 Effects of forage moisture content on various microorganisms and processes in forage.



Biological processes in silage-making usually involve the most readily available nutrients, such as plant sugars. Thus, in both hay and silage systems, the changes that occur are often detrimental to the quality of the forage. As a result of these changes, the following quality parameters may be affected:

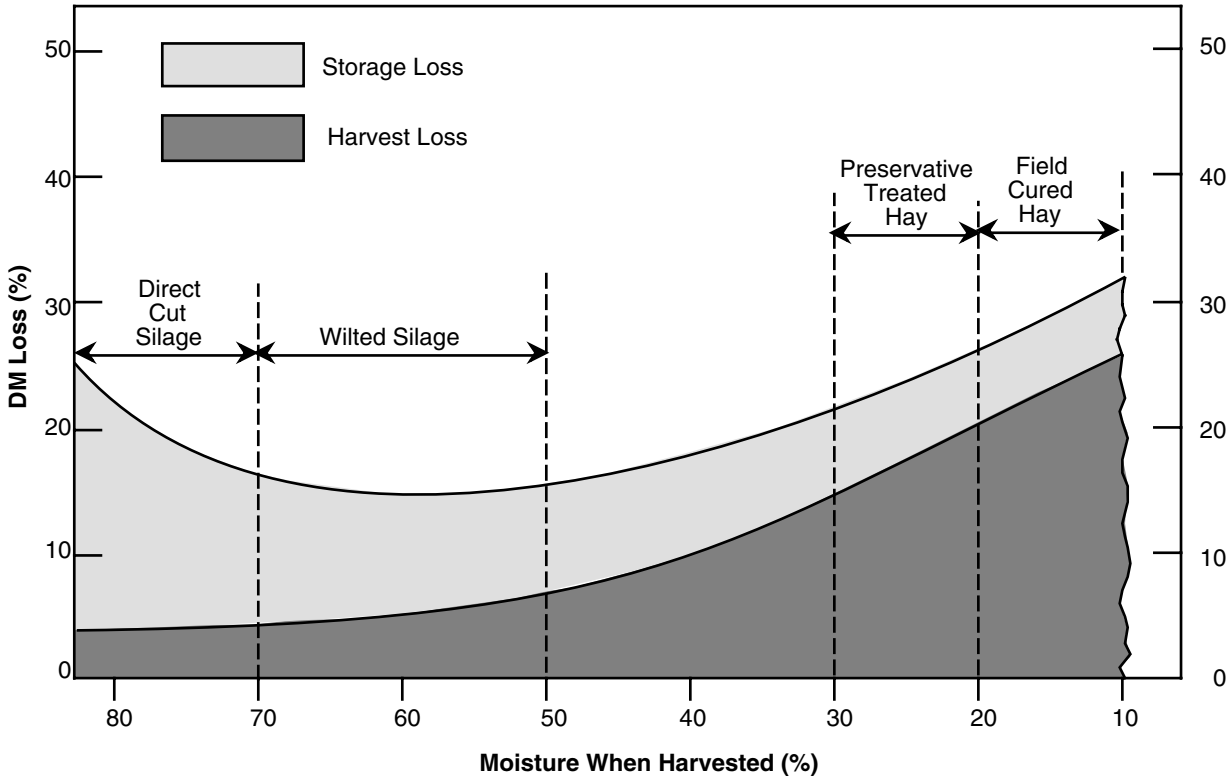
- ADF (Acid Detergent Fiber): Cellulose plus lignin; high ADF correlates with low digestibility and increases as DM is lost.
- NDF (Neutral Detergent Fiber): Hemicellulose plus cellulose plus lignin; high NDF correlates with low dry matter intake and increases as DM is lost.
- CP (Crude Protein):Total nitrogen expressed as a protein equivalent (total nitrogen × 6.25). Loss of leaves decreases CP.
- SP (Soluble Protein): That portion of the crude protein which is readily available for microbial synthesis in the rumen; if large increases in SP occur in silage, animal digestion can be adversely affected.
- ADIP (Acid Detergent Insoluble Protein): bound-nitrogen compounds unavailable for digestion, expressed as a protein equivalent (nitrogen × 6.25). Heating in the silo or in the barn increases ADIP.
- NE_L (Net Energy for Lactation): The energy content of the forage available for milk production, estimated from ADF.

Management

DM losses and quality changes cannot be eliminated in forage preservation, but they can be minimized by utilizing good management practices. Understanding the processes which cause these changes is critical to formulating and following good management practices. Figure 3 shows the proper DM content for well-managed ensiling. The practices for good silage-making are as follows:

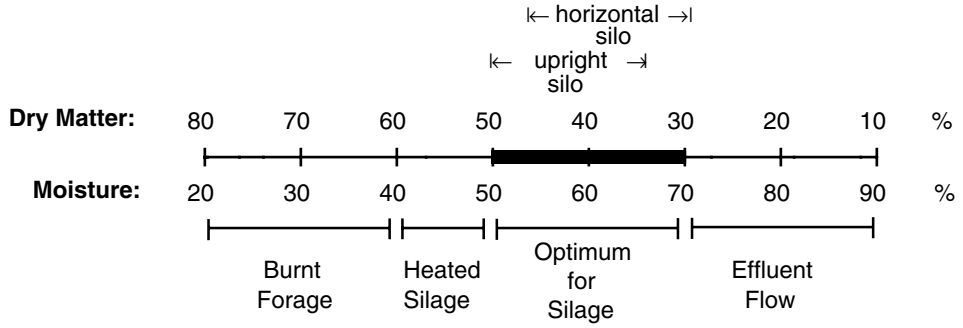
- ☐ Enhance rapid drying in the field.
- ☐ Chop haycrop silage at 3/8 inch theoretical length of cut (TLC), corn silage at 1/4 inch.
- ☐ Ensile at 30%–50% DM content.
- ☐ Fill silo quickly.
- ☐ Compact forage tightly.
- ☐ Seal silo carefully.
- ☐ Leave silo closed for at least two weeks.

Dry matter losses during harvest and storage as dependent on forage moisture content at harvest. **Figure 2**



Source: Hoglund (1964)

Optimum DM content for good silage-making. **Figure 3**



The practices for good silage-making are as follows (continued):

- ☐ Divert surface water away from bunkers.
- ☐ Unload 2–6 inches/day in bunker silos.
- ☐ Leave smooth face on silage.
- ☐ Discard deteriorated silage.

The practices for good hay-making are summarized below.

- ☐ Mow forage early in day.
- ☐ Form into spread swath.
- ☐ Rake or ted at 40%–50% moisture.
- ☐ Bale at 18%–20% moisture.
- ☐ Store hay under cover.

The Biology of Silage Preservation

Section 1

The basic objectives in silage-making are (1) to exclude oxygen from the silage mass and (2) to reduce the pH of the forage rapidly to 3.8–5.0 (depending on DM content and crop type).

Figure 4 shows the sequence of processes that take place in the silo during a successful fermentation. In the *aerobic phase*, oxygen trapped in the air spaces of the silage mass is consumed by plant respiration and aerobic microorganisms. If the silo is well-sealed, little or no oxygen infiltrates into the forage, and it quickly reaches an anaerobic state. In the *lag phase* which follows, plant cell membranes break down, allowing the cell juices to become a growth medium for bacteria. In the *fermentation phase*, the anaerobic lactic acid bacteria begin to grow and multiply rapidly, increasing their numbers to about 1 billion per gram of forage. As the bacteria grow, they use plant sugars and produce lactic and acetic acids, the accumulation of which reduces the pH of the forage. When the pH reaches 3.8–5.0, the bacteria die out, and the silage is in the *stable phase*. In a tight silo, this phase lasts until the silo is opened and silage comes in contact with oxygen.

Detrimental processes may also occur in silage. Plant enzymes are active early in the *fermentation phase* in solubilizing plant proteins. Oxygen may infiltrate from the outside air and extend respiration, causing heating and browning. Undesirable bacteria such as clostridia or listeria may induce spoilage. Seepage may occur if the DM content is too low at ensiling. When the silage is exposed to air, yeast and mold growth causes aerobic deterioration. However, with proper management, these detrimental processes can be minimized or controlled.

Excluding Oxygen from Silage

The first objective of silage-making is to exclude oxygen from the silage mass. When oxygen is present, plant respiration occurs, causing the breakdown of plant sugars to gaseous carbon dioxide and liquid water, and the release of heat, as shown by the following reaction:

$$\underset{\{\text{sugar}\}}{C_6H_{12}O_6} + \underset{\{\text{oxygen}\}}{6\,O_2} \rightarrow \underset{\{\text{carbon dioxide}\}}{6\,CO_2} + \underset{\{\text{water}\}}{6\,H_20} + \underset{\{\text{heat}\}}{1.74\ \text{Mcal/lb sugar}}$$

Respiration results in a loss of available nutrients and energy and thus tends to increase NDF and ADF and to decrease NE_L.

Sequence of phases in the silo for a good fermentation. **Figure 4**

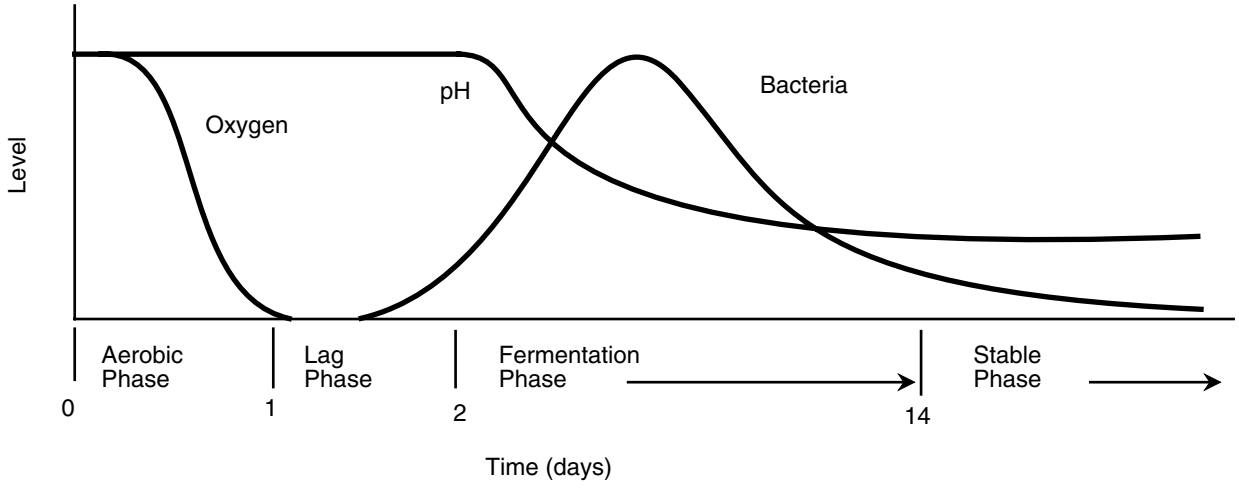


Table 1 Temperature rise (°F) after a silo is tightly sealed at various compaction levels (bulk densities) and DM contents.

Bulk density (lb/ft^3)	DM content (%)					
	20	30	40	50	60	70
20	4.8	5.3	6.0	6.8	7.8	9.0
30	2.5	2.8	3.2	3.7	4.3	5.0
40	1.4	1.6	1.9	2.2	2.5	3.0
50	0.7	0.8	1.0	1.2	1.5	1.8
60	0.2	0.3	0.5	0.6	0.8	1.0

Source: Pitt (1983)

Table 2 Effect of various coatings on oxygen permeability.

Staves tested	Oxygen permeability (cm/(atm-h))
Plain stave sections	3.9
Plastered staves	3.7
Plastered staves, jointed	3.7
Plastered staves with latex masonry paint	2.4
Plastered staves, jointed, with latex masonry paint	1.4
Plastered staves with polystyrene paint	1.8
Plastered staves with epoxy paint	0.4

Source: Lewallen and Brown (1967)

In the silo, plant respiration is limited by the availability of oxygen, which depends on how rapidly the silo is filled, how well the forage is compacted, and how tightly the silo is sealed. The heat released by respiration raises the temperature of the forage. Although a slight rise in temperature to 80°F–90°F is acceptable, a principle of good silage-making is to limit respiration so as to minimize losses and create optimum growth conditions for the lactic acid bacteria. Once filling has begun, the process should remain as continuous as possible, with delays no longer than overnight.

Table 1 shows the temperature rise in a tightly sealed silo as dependent on silage DM content and compaction. Compaction is measured by bulk density, pounds of forage per cubic foot of volume. Heating is less in more compacted forage, because compaction increases bulk density and excludes oxygen. Temperature rise decreases as DM content goes down, because water is a good absorber of heat. Silage temperatures below 90°F indicate good compaction and proper DM content.

Chopping the forage finely helps compaction, but chopping too finely may cause nutritional problems. At least 20% of the particles should exceed 1 inch in length. A 3/8 inch TLC is considered optimum for haycrop silages, 1/4 inch for corn silages. Compaction is generally better in low-NDF forage and therefore varies with forage species and maturity. Applying pressure to the top surface of the forage during loading aids compaction through the entire depth. In a tower silo, this is accomplished by using a distributor and topping off with a layer of wet forage. In a bunker silo, pressure is applied by driving over the surface with a wheel tractor between loads.

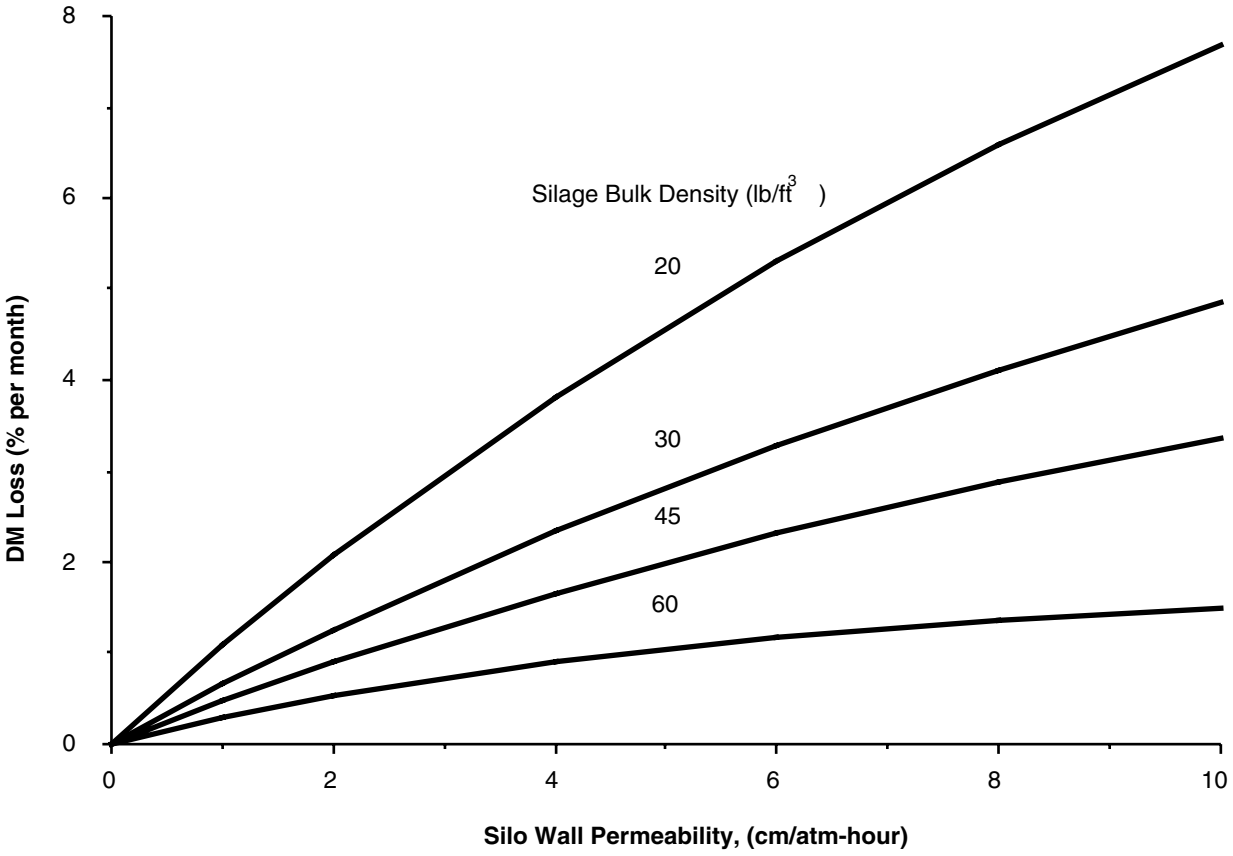
Over the long storage period, oxygen infiltrates the silo through pores or cracks in the silo walls, and through openings and rips in plastic covers. Infiltration extends respiration and causes additional temperature rise. The DM and energy losses due to respiration can be substantial. Figure 5 projects DM losses in a tower silo depending on the ease with which oxygen can penetrate the silo (permeability) and on the bulk density of the forage. Losses are reduced by maintaining a tight seal (reducing permeability) and by enhancing the compaction of the forage (increasing bulk density).

Treatment of concrete silo walls with latex masonry paint, polystyrene paint, or epoxy paint reduces permeability. Table 2 shows the effect of various coatings on the oxygen permeability of silo concrete

staves. Plastering of the walls has little effect in decreasing permeability. The National Silo Association recommends examining the interior surface of a concrete silo every year to evaluate if treatment is required. Silage acids cause softening of concrete, primarily in the bottom 1/3 of a tower silo, where the lateral and frictional forces exerted by the silage mass against the wall are highest. The surface should be treated if it can be easily scratched with a coin. Latex, polystyrene, or epoxy-based paints which penetrate

DM loss in a 20 ft diameter tower silo as dependent on silo wall permeability to oxygen and silage bulk density.

Figure 5



Source: Pitt (1986)

Example of losses and silo quality changes in covered versus uncovered bunker silos.

Table 3

	Temperature at 49 days (°F)	DM losses (%)	pH	Lactic acid (%DM)	Crude protein (%DM)	ADF (%DM)	N fractions (% CP) SP	NH_3-N[b]	ADIP
Covered									
top of silage[a]		4		3.0			20		
bottom of silage[a]		3		3.3			22		
overall average	98	4	4.9	3.2	21	39	20	7	28
Uncovered									
top of silage[a]		51		0.6			11		
bottom of silage[a]		13		2.8			20		
overall average	129	32	6.8	1.7	22	47	16	8	37

[a]The two depths were 1 ft and 4 ft below the top surface.
[b]NH_3-N = ammonia-nitrogen, expressed as a protein equivalent.
[c]Initial DM content was 44%.

Source: Oelberg et al. (1983)

the concrete will remain effective for a number of years. Check for FDA approval of silo coatings before purchasing.

Covering of bunker silos is an important practice for good preservation. Use of plastic covers decreases silo temperatures, DM losses, and silage pH, increases lactic acid content, and lowers ADIP and ADF. Table 3 compares quality of silage in covered and uncovered bunker silos after seven weeks. Quality was lower and losses higher at the top, while covering had a dramatic effect in minimizing losses.

Because oxygen infiltrates through the outer surfaces of the silage, surface area is another factor affecting plant respiration losses. High surface-to-mass ratios mean more spoilage if the silo is not well sealed (see Table 4). Smaller silos, especially bags, have a higher surface-to-mass ratio and are more susceptible to spoilage due to a poor seal. The DM capacities of silos of various sizes are given in Appendices A and C. Table 5 describes practices that minimize respiration losses in four different storage facilities.

Lactic Acid Fermentation

The second basic objective in silage-making is to reduce the pH through the growth of lactic acid bacteria after the silo is sealed. These bacteria ferment plant sugars (the *substrate*) to lactic acid, acetic acid, and several other compounds.

Table 4 Ratio of silo surface area to silage dry matter for various silos.

Silo	Haycrop silage capacity (tons DM)	Surface to mass ratio (ft^2/ton DM)
Tower silos		
20 x 60	160	25
24 x 60	230	22
24 x 80	335	19
Bunker silos		
8 x 30 x 120	170	35
12 x 30 x 120	255	28
12 x 50 x 120	425	24
12 x 50 x 200	710	22
Long Bag		
8 x 90	25	50
Big Round Bale	0.5	170

Table 5 Management practices to minimize respiration losses in silage.

Tower Silo	Bunker Silo	Long Bag	Big Round Bale
Chop at correct TLC.[a]	Chop at correct TLC.[a]	Chop at correct TLC.[a]	—
Fill rapidly.	Fill rapidly.	Fill rapidly.	—
Top off with 1 or more ft. of wet forage.	Compress forage with tractor during filling.	Set filling machine for high compaction	Bale tightly.
Cover top with plastic.	Cover with plastic, seal ends and sides carefully.	Seal ends carefully.	Wrap or seal carefully.
Treat concrete with sealant.	Seal cracks in wall, repair holes in plastic cover.	Repair damaged bags.	Repair damaged bags.

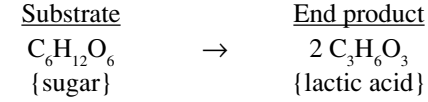
[a]TLC = theoretical length of cut. Chop haycrop silage at 3/8 inch TLC, corn silage at 1/4 inch TLC.

Scientific names of some lactic acid bacteria in silage. **Table 6**

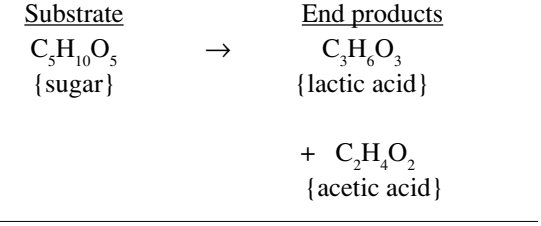
Homofermentative	Heterofermentative
Lactobacillus plantarum	*Lactobacillus brevis*
Lactobacillus casei	*Lactobacillus buchneri*
Pediococcus cerevisiae	*Lactobacillus fermentum*
Pediococcus acidilactici	*Leuconostoc mesenteroides*
Streptococcus faecalis	
Streptococcus lactis	
Streptococcus faecium	

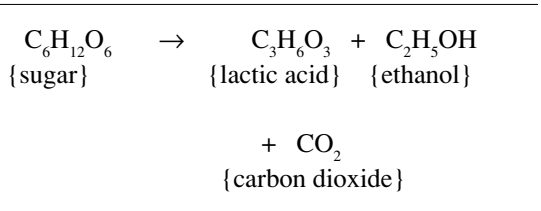
Source: McDonald (1981)

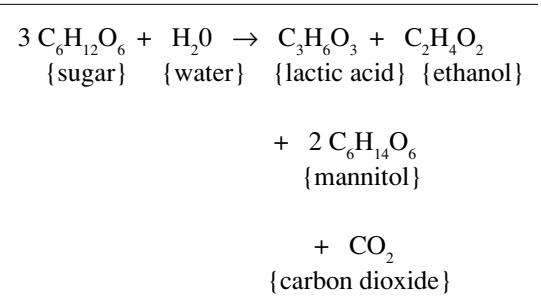
A number of different species of lactic acid bacteria are active in silage, and they are listed in Table 6. *Homofermentative* species produce mostly lactic acid, as in the following reaction:



Heterofermentative species produce lactic acid, as well as significant amounts of acetic acid, mannitol, ethanol and carbon dioxide, as in the following reactions:







Only the acids help reduce silage pH and are consequently most important in silage fermentation. Lactic acid is stronger than acetic acid; this means lactic acid reduces pH more than acetic acid and is therefore more efficient in the preservation process. Carbon dioxide production represents a DM loss. Because homofermentative species produce mostly lactic acid, they are preferable in silage.

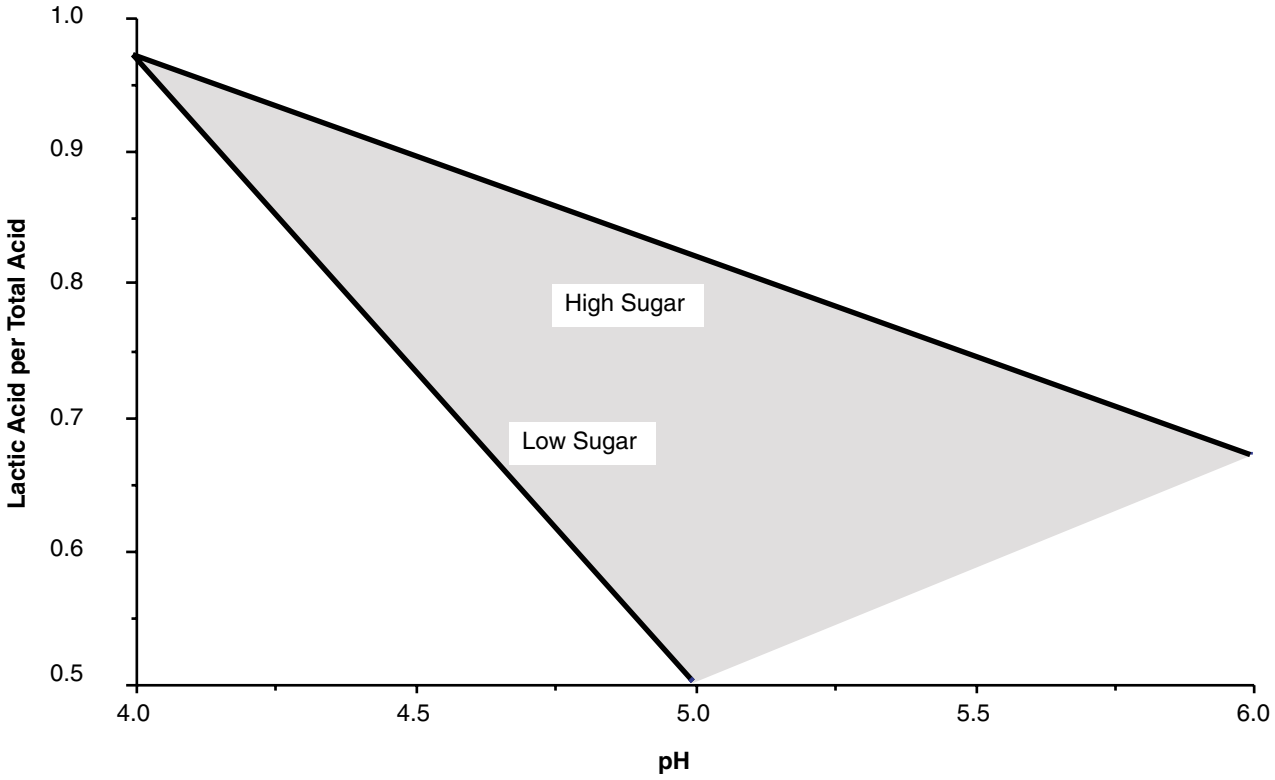
During the fermentation process, different species of lactic acid bacteria become dominant at different times. As a result, the amount of lactic acid produced, as a fraction of total acid produced, changes during the fermentation process. Figure 6 shows that at high pH (at the start of fermentation), bacteria produce a substantial quantity of acetic acid. As the pH decreases, lactic acid becomes the predominant end product. However, if the plant sugar content is low, a smaller fraction of lactic acid is produced. In well-preserved silage, at least 70% of the acids present are lactic acid.

The lactic acid bacteria in silage need sugars to grow. As fermentation proceeds, the sugar content decreases. If sugars are depleted during fermentation, the pH reduction is arrested and may not be sufficient to stabilize the forage.

Maximum pH reduction requires sufficient plant sugars in the forage at ensiling. Two factors govern the sugar requirement for maximum fermentation: DM content and crop species. In low DM forage, bacteria die out at a lower pH; hence a lower pH is needed, requiring more acid, which in turn requires more sugars for conversion to acid. Due to the natural buffering capacity of legumes, the amount of acid needed to reduce the pH from 6 to 4 is greater and requires more sugar than for grasses or corn. Table 7 summarizes the sugar requirements for maximum fermentation of alfalfa, grass, and corn.

Alfalfa typically both has a lower sugar content at harvest and requires more sugar for maximum fermentation. Table 7 shows that incomplete fermentation is likely when alfalfa is ensiled at DM

Figure 6 Lactic acid produced during silage fermentation as a fraction of total acid production, as dependent on forage pH and sugar content.



Source: Pitt et al. (1985b)

Table 7 Sugar requirements for maximum pH reduction, and typical sugar contents in alfalfa, grass, and corn crops at harvest.[a]

DM content (%)	Minimum required initial sugar content (% DM)		
	Alfalfa	Grass	Corn
17	34	28	20
20	25	19	14
25	21	14	10
30	17	10	7
35	14	7	5
40	10	5	4
45	7	3	—
50	6	2	—

[a]Typical sugar contents at harvest, expressed as a percent of DM, are 4%–15% for alfalfa, 10%–20% for grass, and 8%–30% for corn. Boxes show the range in which the typical sugar contents are sufficient for maximum fermentation.

Source: Leibensperger and Pitt (1988)

contents below 35%; in grasses, incomplete fermentation only occurs at DM contents less than 20% (unwilted). Ensiling alfalfa/grass mixtures helps alleviate the low sugar levels/high sugar requirements associated with ensiling pure alfalfa. The sugar content of corn is usually sufficient for maximum pH reduction.

Each forage type exhibits a large range of sugar contents, as shown in the footnote in Table 7. Table 8

lists factors affecting the sugar content of haycrop forage. To conserve sugar for fermentation, harvest management should focus on rapid drying to restrict respiration losses, rather than on maximizing the sugar content at mowing. For example, mowing late in the day may result in higher sugar contents at mowing but causes greater losses due to respiration overnight.

Besides sufficient plant sugars, the attainment of low pH in silage requires the presence of lactic acid bacteria on the harvested forage. A higher number of these bacteria will lower the pH more quickly, once anaerobic conditions are established in the silo. On alfalfa, the numbers of lactic acid bacteria at harvest vary from 100 to 100,000,000 bacteria per gram of forage. Some important facts about the numbers of lactic acid bacteria on haycrop forage are (Muck, 1989):

- ☐ The numbers of bacteria on the growing plant are small.
- ☐ Mowing/conditioning adds about 50 bacteria per gram of forage.
- ☐ Bacterial numbers increase during wilting, more so in warm, moist environmental conditions.
- ☐ Bacterial numbers are highest in the first load of the day.
- ☐ Chopping adds about 1000 bacteria per gram of forage, although this varies with the temperature at harvest.

Table 9 summarizes the lactic acid bacterial numbers expected at ensiling under various wilting and harvesting conditions. Numbers are higher with longer wilting times, warmer temperatures, and lower DM contents at harvest. Bacterial numbers might be considered insufficient when they are less than 10^5 bacteria/gram forage (less than 5 in Table 9). In general, it is difficult to control bacterial numbers on forage entering the silo without the use of an additive.

In summary, lactic acid fermentation requires:

- ☐ Sufficient plant sugars.
- ☐ Lactic acid bacteria on forage.
- ☐ Anaerobic conditions.
- ☐ Proper DM content (30%–50%).

Protein Solubilization

Protein solubilization is a process that converts true protein to soluble, non-protein compounds. Crude protein (CP) is the sum of both non-protein nitrogen

Factors affecting sugar content of haycrop forage before fermentation. **Table 8**

Factor	Effect
Solar radiation on day of cutting.	Sunny periods promote the deposition of sugar in the growing plant.
Hour of cutting.	Sugar levels are higher late in the day, lowest in the morning. However, early mowing is recommended to reduce wilting time.
Length of wilting period.	Plant respiration during drying depletes sugars.
Rain damage in field.	Rain on mowed forage leaches out sugars and increases respiration.
Rate of silo filling.	Delays in attainment of anaerobic conditions extend respiration, decrease sugars.
Compaction of forage.	Good compaction shortens the aerobic phase, leaves more sugars for fermentation.
Sealing of silo.	Good sealing keeps out oxygen, limits sugar loss through respiration.

compounds and true protein, a chain of amino acids. The average mass of an amino acid is 6.25 times the mass of nitrogen in the amino acid. Crude protein is defined as 6.25 times the total nitrogen in the forage, and is therefore calculated as though all nitrogen compounds were true protein.

In the silo, much of the CP is solubilized. Soluble protein (SP) includes ammonia, nitrates, nitrites, free (unlinked) amino acids, amines, amides and peptides (short chains of amino acids). Feeding high-SP silages can cause nutritional problems, because the rumen bacterial requirement for degradable intake protein (DIP) is exceeded and the animal's requirement for undegraded intake protein (UIP) is not met (Shaver and Howard, 1989). This may result in extensive absorption of nitrogen through the rumen wall and subsequent excretion by the animal.

Table 9 Number[a] of lactic acid bacteria on alfalfa at ensiling.

Wilting time (hours)	Conditions during wilting[b]	DM content at harvest (%)							
		25	30	35	40	45	50	55	60
24 or less	Cool	4.6	4.2	3.5	3.3	[3.2	3.2	3.2	3.2][c]
	Warm	5.0	4.6	4.2	3.8	[3.4	3.4	3.4	3.4][c]
24 to 48	Cool	6.0	5.5	5.1	4.7	4.2	3.8	3.4	[3.2][c]
	Warm	7.5	7.0	6.4	5.9	5.3	4.8	4.2	3.7
48 to 72	Very cool	7.3	6.6	5.8	5.1	4.4	3.7	3.0	[2.9][c]
	Cool	6.8	6.4	6.0	5.6	5.2	4.8	4.4	4.0

[a] Each number *x* in the table means there are 10^x lactic acid bacteria per gram of forage at ensiling. Example: $x = 3.5$; $10^{3.5}$ = 3,200 bacteria per gram forage.

[b] "Very cool" means average temperatures of 59°F–66°F during wilting.
"Cool" means average temperatures of 66°F–72°F during wilting.
"Warm" means average temperatures of 72°F–77°F during wilting.

[c] Numbers in brackets [ ] indicate that most of the lactic acid bacteria are supplied by chopping.

Source: Muck (1989)

Table 10 Factors affecting protein solubilization in silage.

Factor	Effect
Crop species	Leguminous protein, especially that of alfalfa, is more rapidly solubilized in the silo.
Silage temperature	Solubilization rate doubles with a 20°F increase in temperature.
DM content	Solubilization is fastest in direct-cut forage (20% DM content); the rate is reduced by 60% at 50% DM content.
pH	Solubilization is fastest at pH 6; the rate is decreased by 85% at pH 4.
Time in silo	Proteases lose their activity after 1–2 weeks in the silo. Most solubilization occurs in the first few days of ensiling.

Increases in soluble protein (SP) content (as a % of crude protein) during the ensiling process.

Table 11

Silage temperature (°F)	Legume DM content (%) 20	30	40	50	Grass DM content (%) 20	30	40	50
70	32	29	25	19	21	19	16	12
85	46	45	40	33	32	30	26	21
100	56	56	56	52	49	48	44	36

Strategies for inhibiting protein solubilization.

Table 12

Strategy	Implementation
Rapid reduction in pH.	Establish anaerobic conditions quickly: rapid filling, good compaction and sealing.
Maximum pH reduction.	Promote maximum fermentation by conserving plant sugars: rapid wilting and filling, good compaction and sealing.
Limit maximum temperature in silo.	Minimize respiration in silo: rapid filling, good compaction and sealing.

Solubilization of true protein occurs in the silo due to the action of plant enzymes called proteases. In the growing plant, these enzymes serve a normal but limited function. In the harvested plant, proteases are released when cell membranes break down (see *lag phase,* pg. 5), and their activity increases dramatically. Table 10 shows that the extent of solubilization in the silo depends on several factors, including crop species, silage temperature, DM content, pH, and time in the silo.

During the ensilage process, changes in temperature and pH affect the solubilization rate. Table 11 lists average increases in SP contents (expressed as a percent of CP) under various temperature and DM conditions. SP increases are greater at warm temperatures, at low DM contents, and in legumes than in grasses.

For example, consider a 30% DM legume ensiled with an SP of 25% of CP at 70°F. From Table 11, the increase in soluble protein during ensiling is 29% for a legume at 30% DM and 70°F. Thus, the SP will increase to 25 + 29 = 54%. If the silage were at 85°F, the SP increase would be 25 + 45 = 70%. Controlling silage temperature is therefore critical for minimizing protein solubilization. Strategies for inhibiting protein solubilization are shown in Table 12.

Clostridial Spoilage

Clostridia are undesirable bacteria that can grow in low-DM silage when oxygen is absent (anaerobic conditions). These bacteria normally live in manure and soil, and their spores may be present in harvested forage. Some species of clostridia (see Table 13) ferment lactic acid and sugars to butyric acid, carbon dioxide, and hydrogen gas as in the following reactions:

$$\underset{\{\text{sugar}\}}{C_6H_{12}O_6} \rightarrow \underset{\{\text{butyric acid}\}}{C_3H_7COOH} + \underset{\{\text{carbon dioxide}\}}{2\,CO_2} + \underset{\{\text{hydrogen gas}\}}{2\,H_2}$$

$$\underset{\{\text{lactic acid}\}}{2\,C_3H_6O_3} \rightarrow \underset{\{\text{butyric acid}\}}{C_3H_7COOH} + \underset{\{\text{carbon dioxide}\}}{2\,CO_2} + \underset{\{\text{hydrogen gas}\}}{2H_2}$$

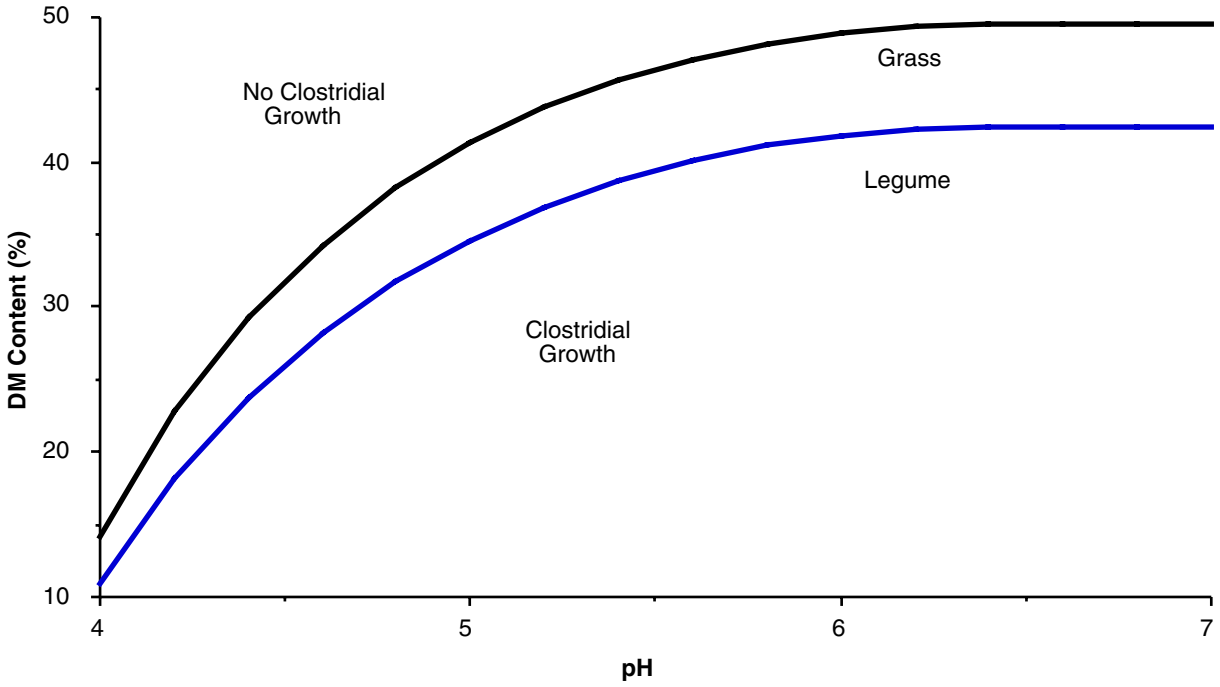
Other species of clostridia (see Table 13) ferment free amino acids to a variety of compounds including acetic acid and ammonia as shown in the following reaction:

Table 13 Clostridial species in silage.

Species	Characteristics
Clostridium tyrobutyricum *Clostridium sphenoides*	Ferment sugars, lactic acid.
Clostridium bifermentans *Clostridium sporogenes*	Ferment amino acids.
Clostridium perfringens	Ferments sugars, lactic acid, and amino acids. Produces toxins.

Source: McDonald (1981)

Figure 7 Clostridial growth as determined by pH, DM content, and forage type.



Source: Leibensperger and Pitt (1987)

$$CH_3CHNH_2COOH + 2\,CH_2NH_2COOH$$
{amino acid, alanine} {amino acid, glycine}

$$+ H_2O \rightarrow 3\,C_2H_4O_2 + 3\,NH_3$$
{water} {acetic acid} {ammonia}

Production of carbon dioxide and hydrogen gas represents a loss of digestible DM and energy. Butyric acid is weaker than lactic acid, and only 1 unit of butyric acid is produced from 2 units of lactic acid; this tends to raise the pH of the forage. Production of ammonia also raises the pH, and high ammonia and butyric acid levels can depress feed intake. Clostridial fermentation also produces compounds such as putrescine and cadaverine, and may result in a toxic silage that causes animal sickness or death.

The characteristics of a clostridial silage include:

- ☐ pH above 5.0.
- ☐ Ammonia-nitrogen greater than 10% of total nitrogen.
- ☐ More butyric acid than lactic acid.
- ☐ Strong, rancid odor.

The effects of a clostridial fermentation are:

- ☐ Poorly preserved forage.
- ☐ High DM losses in the silo.
- ☐ Low DM intake by the animal.
- ☐ Poor utilization of silage nitrogen by the ruminant.

Whether clostridia dominate in silage depends on several factors:

1. *Clostridia cannot tolerate dry conditions*. They are rarely a factor when forage DM content is above 30%.
2. *Clostridia are less tolerant of acid conditions* than are lactic acid bacteria. A lower pH is needed to restrict clostridial spoilage as forage DM content decreases (see Figure 7). For a given DM content, a lower pH is needed in grass silage than in legume silage. A high pH in wet forage signifies clostridial activity. Rapid and extensive reduction in pH prevents clostridial spoilage.
3. *High sugar content of the forage* at ensiling reduces the potential of clostridia, because it promotes maximum reduction in pH through lactic acid fermentation. However, in low-DM legume forages, there are frequently insufficient sugars to support maximum fermentation (see Table 7, pg. 10).
4. *Crops of low buffering capacity* such as grasses and corn are more likely to undergo maximum fermentation to the lowest possible pH and hence are less prone to clostridial spoilage (see Table 7, pg. 10).
5. *Clostridia cannot grow in the presence of oxygen*. Even so, the attainment of anaerobic conditions is a basic objective in silage-making.
6. *High numbers of lactic acid bacteria* speed the rate of pH decline and thereby inhibit clostridial spoilage.
7. *Soil contamination* of the forage during mechanical operations in the field increases clostridial spores and the likelihood of spoilage.

Guidelines for preventing clostridial spoilage are as follows:

- ☐ Drying the forage to at least 30% DM reduces the chance of clostridial spoilage.
- ☐ With forage below 30% DM content, some type of additive may be necessary (see **Silage Additives**, pg. 30).

Effluent Production

If the DM content of the forage at ensiling is too low, effluent (seepage) will be produced from the silage. In general, DM contents above 30% in bunker silos and 35% in tower silos will prevent effluent flow, although the limiting DM content varies somewhat with silo dimensions. Runoff of rainwater into the silage mass in a bunker silo also results in effluent flow.

Silage effluent contains about 5% solids including plant sugars and soluble protein. Effluent production from silage results in a loss of valuable nutrients and energy from the forage. Effluent also serves as an ideal growth medium for microorganisms. The biological oxygen demand (BOD) of silage effluent, a measure of the oxygen required to degrade the effluent by microorganisms, can be as high as 50,000 mg oxygen per liter of effluent (the BOD of domestic sewage is 500 mg per liter). Thus, the effluent generates strong odors and engenders high populations of bacteria, yeasts, molds, and possibly listeria; it may create an environmental hazard around the silo and disrupt the ecology of nearby streams and ponds.

Effluent which has flowed from a silo should be collected and removed or drained to the manure pit. Spreading silage effluent on the fields is an effective way to dispose of it, and at the same time, adds fertilizer to the soil. However, in hot weather effluent can scorch growing plants. Most of the effluent from bunker silos is produced in the first week after ensiling, although flow may continue for up to several months. The amount of effluent produced increases as forage DM content decreases, as shown for grass crops in Table 14.

Effluent produced and resulting DM loss from grass crops stored in bunker silos. **Table 14**

DM content (%)	Effluent produced (gallons per wet ton of silage)	DM loss from effluent (%)
30	0	0
25	5	0.4
20	15	1.6
15 (direct cut)	50	7.2

Source: Bastiman (1976)

From Table 14, the effluent produced from 200 tons of 25% DM silage totals 5 × 200 = 1,000 gallons. For direct-cut silage, 200 tons of silage yields 50 × 200 = 10,000 gallons of effluent; this would require some sort of storage vessel.

In a tower silo, effluent is produced more slowly, but a greater quantity is generated for a given DM content, because the pressure from overlying silage tends to compact the silage and squeeze out the effluent. Chopping the forage at a small length of cut results in more effluent, while mature haycrop forage yields less effluent. Forage DM content primarily determines how much effluent will be produced. The height and diameter of tower silos also affect the production of effluent; the required minimum DM content to prevent effluent flow increases as the silo diameter and height increase (see Table 15).

Greater pressures exist at greater depths in a tower silo. Most effluent production occurs at the bottom of a tower silo, while little or no production takes place in the top 10 ft. Thus, a layer of wet forage at the bottom will yield effluent, but the same layer near the top will not produce effluent.

Listeria

Listeria monocytogenes bacteria cause listeriosis, a disease dangerous to both animals and humans. In animals, listeriosis causes encephalitis (inflammation of the brain tissue), a nervous disorder called "circling disease," abortion, and death. Silage has been strongly implicated as a source of listeriosis in farm animals. A survey in Britain showed that 3%–6% of bunker silos and 22% of round bale silages were infected with listeria (Griffiths, 1989).

To grow in silage, listeria require oxygen and a pH above 5.5. Small pockets of silage at high pH may contain listeria. Listeria do not grow in a well-sealed silo or in silage that has undergone a good fermentation. In highly aerated, poorly preserved forage, the more aggressive yeasts and molds often dominate. Listeria may be present where there is a slow infiltration of oxygen into the silage, such as at the end of a silage bag or near a puncture in the plastic.

Listeria can grow over a wide range of temperatures (40°F–110°F) and silage DM contents (20%–75%), although DM contents above 80% (baling levels) inhibit their growth. Listeria are sometimes present on the ground near a silo where silage effluent has collected.

To prevent listeria growth in silage:

- ☐ Maintain anaerobic conditions through good compaction and tight sealing.
- ☐ Allow the forage two weeks to ferment.
- ☐ Ensile forage in the proper DM range (30%–50% DM).
- ☐ Keep a clean environment in the barn and around the silo.
- ☐ Discard silage that appears spoiled through contact with oxygen.

Aerobic Deterioration

Aerobic deterioration occurs when silage is exposed to air, changing its chemical composition, pH, and temperature. As a result, both the quantity and quality of the forage are reduced. Yeasts, molds, and aerobic bacteria (see Table 16), present in the silage but dormant in a tightly-sealed silo, consume plant sugars

Table 15 Minimum DM content to prevent effluent flow from tower silos.

Silo height (ft)	Silo diameter (ft)				
	10	15	20	25	30
20	22	24	26	26	26
30	24	28	29	30	31
40	26	30	32	34	35
50		32	34	37	38
60		33	37	39	40
70				41	43
80				43	46

Source: Pitt and Parlange (1987)

Microbial genera associated with aerobic deterioration. **Table 16**

Fungi		
Yeasts	**Molds**	**Aerobic bacteria**
Candida	*Aspergillus*	*Acetobacter*
Cryptococcus	*Fusarium*	*Bacillus*
Hansenula	*Geotrichum*	*Streptomyces*
Pichia	*Monascus*	
Saccharomyces	*Mucor*	
	Penicillium	
	Rhizopus	
	Trichoderma	

Source: McDonald (1981)

and fermentation end products and produce carbon dioxide, water, and heat. This results in rises in temperature and pH, a loss of digestible nutrients, increases in NDF and ADF, and decreases in NE_L. Aerobic deterioration is not a "secondary fermentation," since fermentation only takes place in the absence of oxygen. Deteriorated forage is usually white or discolored, and may contain toxins which are poisonous at certain levels of intake. Moldy feed has a high estrogen content and can reduce resistance to infections, particularly mastitis.

Aerobic stability (or bunk life) is the length of time a silage remains at normal temperatures when exposed to air, and varies from less than one hour to several days. A number of factors affect bunk life:

1. *Presence of oxygen.* Aerobic microbial growth rates decrease as oxygen levels drop below 5% (the oxygen level in air is 21%). Ensiling conditions which permit oxygen infiltration (poor compaction and poor sealing) enhance the growth of aerobic organisms and decrease bunk life when the silo is opened.
2. *Presence of carbon dioxide.* Buildup of carbon dioxide in the silo inhibits aerobic microbial growth, especially when concentrations exceed 20%.
3. *Aerobic microbial numbers.* The greater the number of aerobic organisms present in the silage, the faster the silage will deteriorate in air. Poorly sealed silos promote growth of these organisms during storage. Mold, spores, or yeasts may perennially contaminate the silo until it is cleaned.
4. *Forage DM content.* Higher DM forage characteristically has a lower bunk life, in part because the forage is more difficult to compact and has a greater tendency to heat (see Table 1, pg. 6).
5. *Temperature.* Higher temperatures at ensiling, during storage, and while unloading increase microbial growth rates. Bunk life is lower in the summer months. However, the aerobic organisms die out when temperatures exceed 110°F–140°F.
6. *Forage species.* Legume silages are generally more stable than grass or corn silages. Legume silage stability apparently results from the high concentrations of fermentation acids (see below), the low residual sugar content after fermentation, and the production during fermentation of compounds that improve bunk life.
7. *Concentration of fermentation acids.* Lactic acid, acetic acid, and butyric acid (clostridial silages) produced during fermentation suppress aerobic microbial growth, especially when combined with a low pH. Highly buffered crops (legumes) undergoing maximum pH reduction (see Table 7, pg. 10) are more aerobically stable. Less buffered crops (corn silage), or crops undergoing incomplete fermentation due to insufficient sugars (see Table 7, pg. 10) tend to be less aerobically stable.

To enhance the bunk life of silage:

- ☐ Fill silo rapidly; no delays longer than overnight if possible.
- ☐ Exclude oxygen during storage through good compaction and sealing.
- ☐ Ensile forage at proper DM content (30%–50%).
- ☐ Keep the silo sealed for at least two weeks to allow maximum fermentation.
- ☐ Promote high sugar levels to obtain maximum fermentation, using rapid wilting and filling, good compaction, and tight sealing.
- ☐ Limit time of exposure to oxygen during unloading. For bunker silos, silo size and animal needs should be matched to remove at least 2 inches of material per day in cool weather and 6 inches per day in hot weather (see **Appendix C,** pg. 47). Feeding out half the face of a bunker silo

may be a good means to achieve the necessary unloading rate.

- ☐ Maintain a smooth face on the surface of silage being unloaded from a bunker silo. This reduces the infiltration of oxygen into the exposed surface.

Browning Reactions

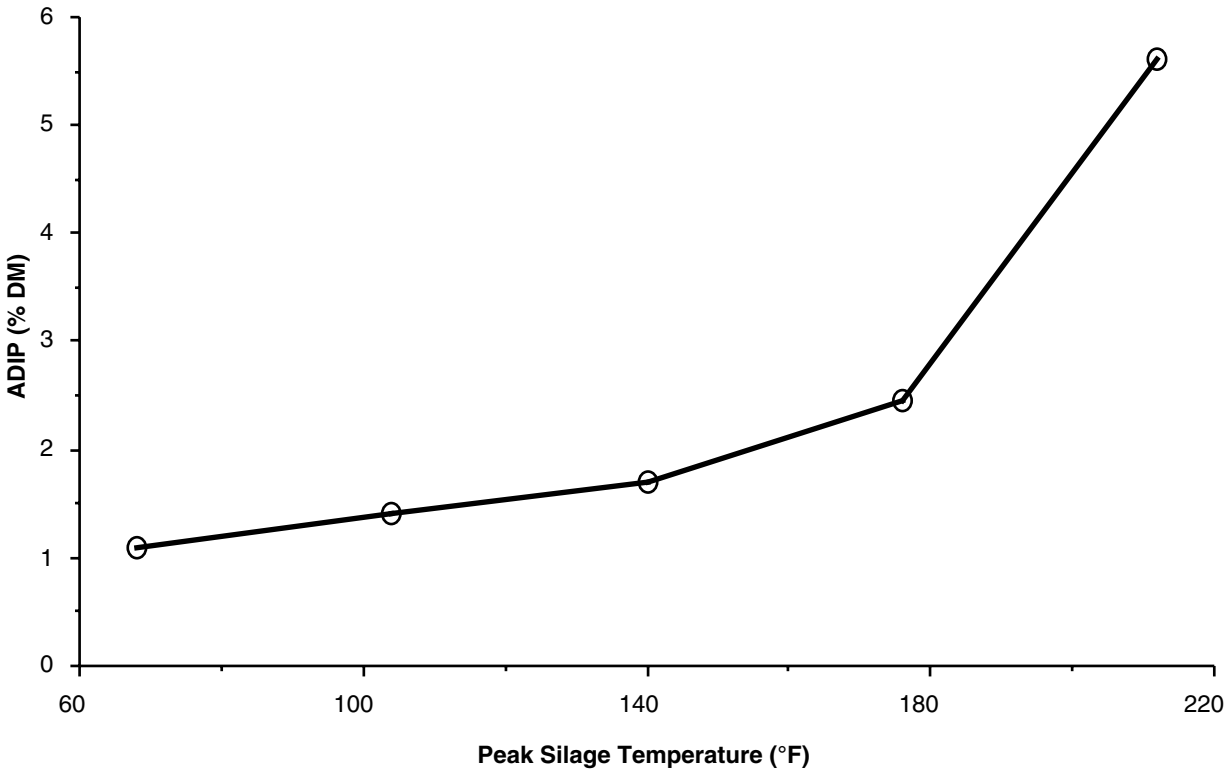
Browning reactions, also called caramelization, non-enzymic browning, or Maillard reactions, occur in many silages and are detrimental to the quality and digestibility of forage. In these reactions, proteins and amino acids combine with plant sugars (usually derived from hemicellulose) to form a brown polymer resembling lignin. This results in increased levels of ADF and ADIP (bound protein), and reduced digestibility and NE_L.

Figure 8 shows the effect of temperature on ADIP content, an indicator of the extent of browning (ADIP levels also depend on time spent at a particular temperature). Drier forage tends to brown, because it does not compact as well and is more prone to heating than wetter forage (see Table 1, pg. 6). Forages in the range of 50%–80% DM are most susceptible to browning (see Figure 1, pg. 2), but because these reactions require water, browning is inhibited at normal baled-hay moisture levels (above 80% DM). Browning reactions occur slowly at 70°F; rises in temperature due to respiration in the silo or during unloading will accelerate the reactions. About 40% of haycrop silages contain elevated ADIP contents. Corn silage (not treated with ammonia or urea) browns less than haycrop silages, apparently due to the low CP contents of corn (Goering and Adams, 1973).

Browning reactions release heat (i.e. they are *exothermic*). The resulting rise in temperature accelerates the reactions further. An upward spiral in temperature can occur that eventually results in spontaneous combustion. Severe browning causes both hay and silage fires.

The best way to inhibit browning reactions is to minimize the heating that occurs immediately after

Figure 8 Acid detergent insoluble protein (ADIP) in legume forage as dependent on silage temperature.



Source: Van Soest (1981)

Summary of good silage-making practices. **Table 17**

Practice	Reason	Benefits
Minimize drying time.	Reduce respiration.	Reduced nutrient and energy losses. More sugar for fermentation. Lower silage pH.
Chop at correct TLC.[a] Fill silo quickly. Enhance compaction. Seal silo carefully.	Minimize exposure to oxygen.	Reduced nutrient and energy losses. More sugar for fermentation. Reduced silo temperatures. Less heat damage (browning). Faster pH decline. More extensive pH decline. Better aerobic stability. Less chance of listeria. Less protein solubilization.
Ensile at 30%–50% DM content.	Optimize fermentation.	Reduced nutrient and energy losses. Proper silo temperatures. Less heat damage (browning). Control clostridia. Prevent effluent flow.
Leave silo sealed for at least 14 days.	Allow complete fermentation.	Lower silage pH. More fermentation acids. Better aerobic stability. Less chance of listeria.
Unload 2–6 in./day. Keep smooth surface.	Stay ahead of spoilage.	Limit aerobic deterioration.
Discard deteriorated silage.	Avoid animal health problems.	Prevent toxic poisoning, mycotic infections. Prevent listeriosis, clostridial toxins.

[a]TLC is theoretical length of cut. Chop haycrop silage at 3/8 inch TLC, corn silage at 1/4 inch TLC.

loading. This heating is directly related to oxygen in silage. To minimize oxygen in silage, follow the guidelines below:

- ☐ Ensile forage at proper dry matter level (30%–50% DM).
- ☐ Fill silo quickly.
- ☐ Provide good compaction, tight sealing.

Silage Gases

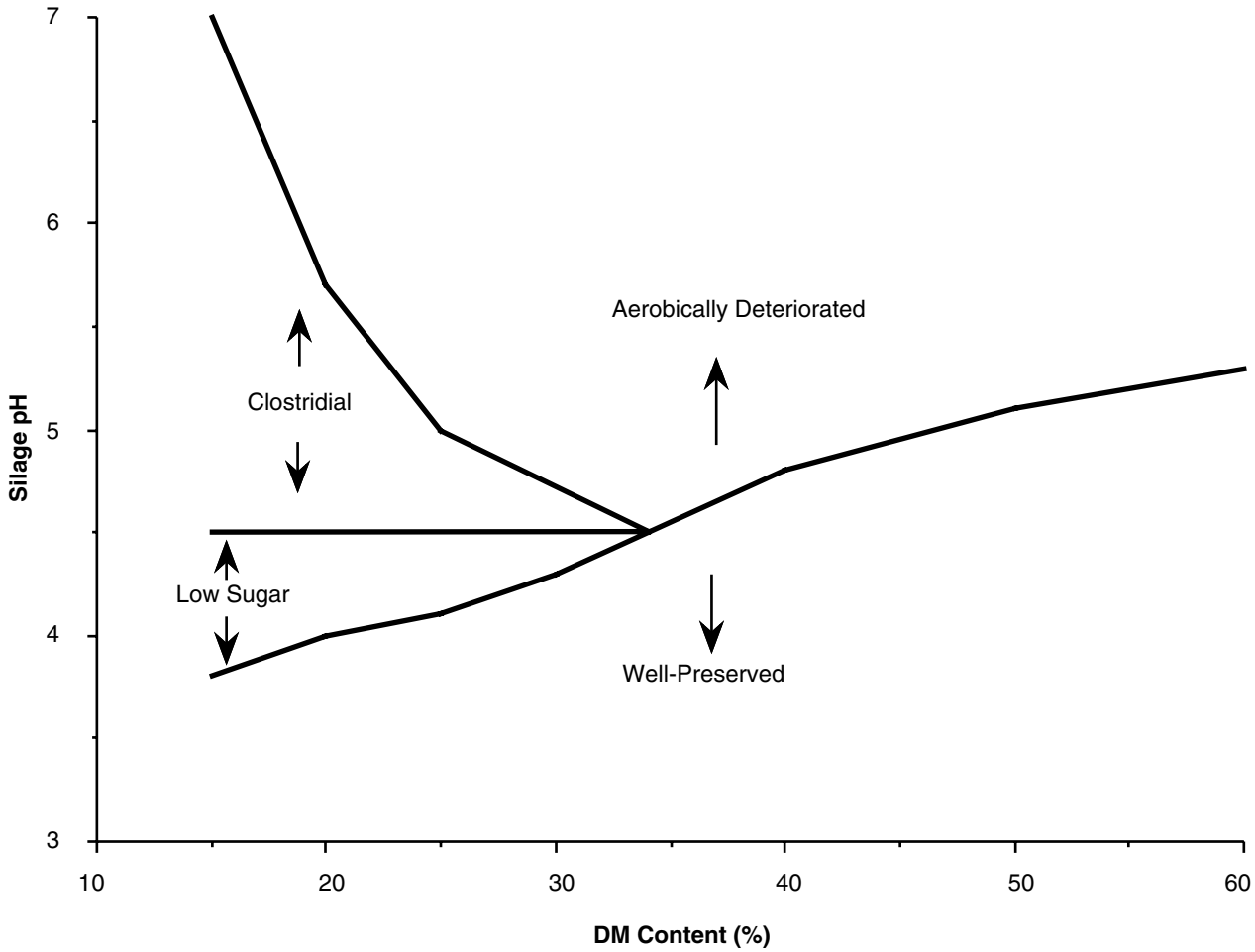
The carbon dioxide given off by plant respiration and bacterial fermentation may accumulate in the silo and create a very dangerous environment for humans. Nitrates and nitrites stored in the plant may also be given off as gases. Inhaling these gases will burn lungs and may cause death in only a few minutes. Nitrate and nitrite gases are especially dangerous in grasses or corn which have been heavily fertilized or exposed to rain before harvest following a period of drought. The greatest danger occurs in the first 12–60 hours after filling the silo.

To prevent poisoning from gases in upright silos, run the silage blower or the unloader for 15–20 minutes before entering the silo. Watch out for yellowish gases and never enter the silo alone during the danger period.

Summary

Good silage-making requires good management. Table 17 provides a summary of silage-making practices

Figure 9 Silage pH as an indicator of preservation.



that lead to better preservation, lower losses, higher forage quality, and improved animal performance.

Silage pH can serve as an indicator of the quality of preservation, when combined with measurement of DM content (see Figure 9). pH shows whether the silage is well-preserved, clostridial, or aerobically deteriorated, and whether low sugar content limited the fermentation.

Preservation of Hay

Section 2

Unlike silage preservation, in which storage management is most critical, good preservation of hay depends primarily on handling and harvest management. The drying rate, mechanical handling of the forage, and moisture content at baling all impact the quantity and quality of the hay. With proper management, little or no degradation takes place in the hay during storage.

Goals in Hay Storage

The basic objective in hay-making is to reduce the moisture content of the forage rapidly and to the proper levels so as to inhibit biological and chemical reactions (see Figure 1, pg. 2). Processes to be controlled or prohibited in hay storage include mold growth and browning reactions as described below:

1. *Mold growth* (see **Aerobic Deterioration**, pg. 16). In the range of 20%–35% moisture content, molds grow as the predominant microorganisms in hay. Mold growth is undesirable because:

- ☐ Molds consume crop nutrients, producing carbon dioxide and water, and causing loss of DM, digestible nutrients, and energy.
- ☐ Mold respiration causes heating that may lead to hay fires.
- ☐ Molds can produce toxins that are detrimental to animal health and that decrease feed intake.
- ☐ Molds produce spores that, if inhaled by farm workers, can cause lung disease.
- ☐ The presence of molds reduces the value of hay sold.

2. *Browning reactions* (see also **Browning Reactions**, pg. 18). If mold growth heats the hay to 100°F or higher, severe browning reactions commence. These reactions combine amino acids and sugars to form ADIP. Browning reactions release heat that may result in an upward spiral in temperature. Browning reactions are undesirable because:

- ☐ Browning reactions cause increases in ADF and ADIP; if sufficiently extensive, this decreases the digestibility of the forage.
- ☐ Browning reactions, when widespread and severe, can lead to spontaneous combustion and hay fires.

Changes in Hay During Storage

As a consequence of mold growth during storage, losses can occur in nonstructural carbohydrates and crude protein, and ADIP content increases if browning occurs. Table 18 gives an example of these changes as dependent on moisture content at harvest. Above 20% moisture content, losses and quality deterioration due

Changes in untreated alfalfa hay composition during six-month storage. **Table 18**

Hay moisture content at harvest (%)	DM loss (%)	Digestible DM loss (%)	Crude protein loss (%)	Increase in ADIP (%)	Increase in NDF content (% DM)
11–20	5	6	6	1	1
20–25	8	12	9	7	4
25–34	11	14	8	9	5

Note: Losses are expressed in terms of percent of initial content.

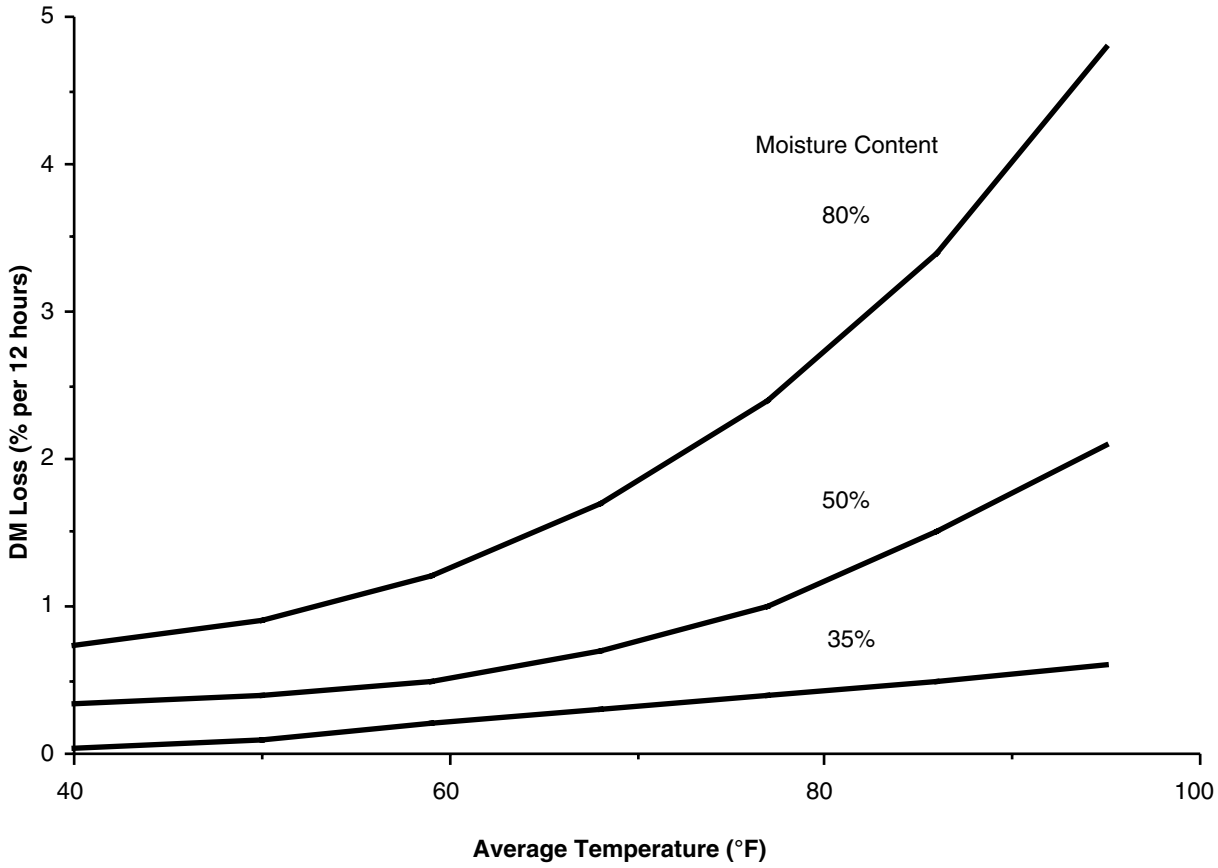
Source: Rotz and Abrams (1988)

Table 19 Final moisture content (%) of baled hay as dependent on air temperature and relative humidity.

Temperature (°F)	Relative humidity (%)			
	30	50	70	90
70	10	13	21	39
80	8	12	20	38
85	7	10	18	37
95	5	8	16	36

Source: Hill et al. (1976)

Figure 10 Rate of DM loss from plant respiration in the field as dependent on forage moisture content and average air temperature.



Source: Rotz et al. (1989)

to mold growth and browning are much greater. Heating also increases when bale density is higher (Buckmaster et al., 1989).

During storage, hay loses moisture until the moisture content reaches 8%–15%, depending on atmospheric conditions in the storage structure (see Table 19). Relative humidity plays a more important role than temperature in determining final moisture content. The moisture content of hay remains low as long as water is not absorbed from the ground, rain, or moist air. Indoor storage helps prevent water absorption and improves preservation. For information on barn-drying hay, see (Campbell, 1988).

Field Losses and Quality Changes

Losses of nutrients during drying in the field result in substantial changes in forage quantity and quality (see Figure 2, pg. 3). These losses are associated with:

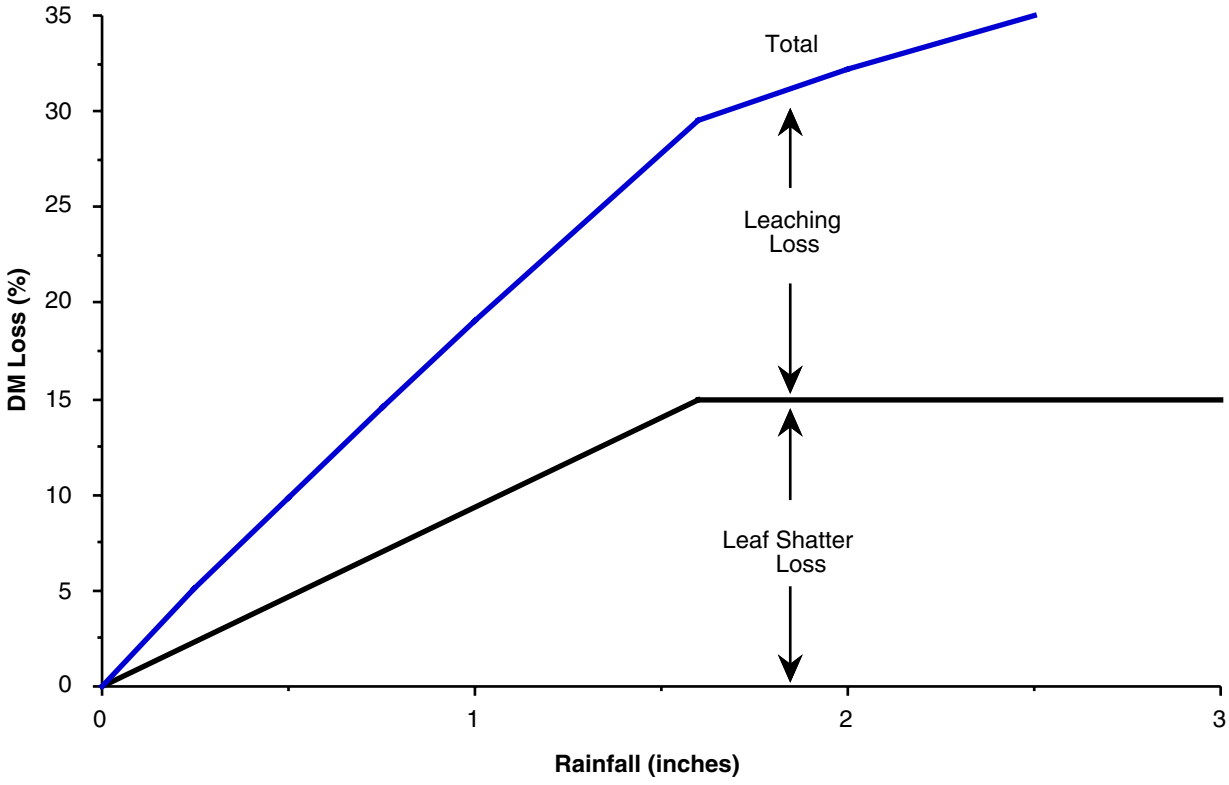
1. *Plant respiration.* Respiration converts plant sugars to water and carbon dioxide, increasing NDF and ADF and decreasing NE_L. As shown in Figure 10, respiration is most active at cutting (approximately 80% moisture content) and increases with temperature. Respiration slows as moisture content decreases and becomes inhibited at moisture contents of 20% or below. A rapid attainment of baling moisture limits respiration losses during drying. Typically, respiration DM losses are 3%–4% per day initially, with a total loss of 10%–15%.

2. *Rain damage.* Rain falling on hay before baling leaches out soluble nutrients and reactivates plant respiration. Hard rain can also shatter leaves, causing additional losses (see Table 20). As shown in Figure 11, significant losses occur from leaching and leaf shatter, even in a light rainfall (1/4 inch). Avoiding rain damage is a goal in hay preservation, but delayed cutting should be balanced against the lower feeding value of late-cut hay.

3. *Mowing/conditioning, raking/tedding, and baling.* Small quantities of plant material, primarily leaves,

DM losses from leaching of nutrients and from leaf shatter during rainfall of varying amounts.

Figure 11



Source: Rotz et al. (1989)

Changes in alfalfa quality with rain damage.

Table 20

	Crude protein (%)	In vitro DM digestibility (%)	NDF (%)	DM yield (tons/acre)
standing crop	23	70	43	2.0
hay—no rain damage	20	64	46	1.7
hay—rain damage	20	57	54	1.5

Source: Collins (1988)

disconnect and drop during mowing/conditioning. Further losses occur during raking or tedding, and these losses increase at lower moisture content. At baling moisture, brittle leaves and petioles easily shatter during mechanical agitation. Leaf loss is especially detrimental to forage quality because the leaves contain a large share of the crop nutrients (see Table 21).

Table 21 demonstrates that carrying out field operations at the correct moisture content is critical to minimizing field losses. Raking/tedding should be performed at about 50% moisture content, at which a significant increase in drying rate is obtained without substantial losses. The optimum moisture content for baling is 18%–20%; this minimizes losses while permitting safe storage (without the use of an additive). Overdrying forage to moisture contents below 18%–20% is unnecessary for good preservation and results in greatly elevated DM losses, especially leaf losses.

Factors Affecting Field Drying Rates

To minimize exposure to the environment and respiration losses in the field, the fastest possible drying is desirable. A number of different factors affect drying rate and total drying time:

1. *Weather parameters*

- ☐ Temperature.
- ☐ Relative humidity.
- ☐ Solar radiation.
- ☐ Wind speed.
- ☐ Soil moisture content.
- ☐ Rain.

Table 21 Losses from alfalfa during harvest operations.

Operation	% of DM lost	% of leaves lost
Mowing	1	2
Mowing/conditioning:		
reciprocating mower, fluted rolls	2	3
disc mower, fluted rolls	3	4
disc mower, flail conditioner	4	5
Raking:		
at 70% moisture	2	2
at 60% moisture	2	3
at 50% moisture	3	5
at 33% moisture	7	12
at 20% moisture	12	21
Tedding:		
at 70% moisture	1	2
at 60% moisture	1	3
at 50% moisture	3	5
at 33% moisture	6	12
at 20% moisture	11	21
Baling, pickup + chamber:		
at 25% moisture[a]	3	4
at 20% moisture	4	6
at 12% moisture	6	8
Baling at 18% moisture:		
conventional square baler/ejector	5	8
round, variable chamber	6	10
round, fixed chamber	13	21
Stack wagon	15	24
Total	7–31	12–50

[a]Requires a preservative for safe storage.

Sources: Kjelgaard (1979)
Rotz (1989)
Hundtoft (1965)

Hours to dry alfalfa from 80% to 20% moisture content in constant environmental conditions. **Table 22**

Sun [a]	Soil conditions[b]	Air temperature (°F) 50	60	70	80	90
Cloudy	**Wet**	44	41	38	35	33
Cloudy	**Dry**	36	34	31	29	27
Sunny	**Wet**	16	16	15	15	15
Sunny	**Dry**	14	13	13	12	12

[a] cloudy = 100 Btu/hr-ft² solar radiation
sunny = 280 Btu/hr-ft² solar radiation
[b] wet soil = 20% moisture content
dry soil = 9% moisture content

Source: Rotz and Chen (1985)

2. *Crop parameters*

- ☐ Forage species (grasses dry faster than legumes; alfalfa dries faster than red clover).
- ☐ Maturity (mature haycrops dry faster).
- ☐ Yields (heavy yields slow drying).
- ☐ Current crop moisture content (drying rate decreases as moisture content decreases).

3. *Management parameters*

- ☐ Time of mowing (mowing early in day allows full day's drying).
- ☐ Use of weather forecasts to plan operations.
- ☐ Spread or windrowed swath (spread swaths dry faster).
- ☐ Raking or tedding (exposes wet underlayer and speeds drying).
- ☐ Swath structure (loose swaths dry faster).
- ☐ Windrow inversion (exposes wet underlayer and speeds drying).

Drying rates increase with temperature, solar radiation, and wind speed and decrease with relative humidity and soil moisture content. Sunlight and air temperature are the principal factors affecting drying rate (see Table 22). On a dry soil with an air temperature of 80°F, drying takes about 2.5 times longer in cloudy conditions (29 hours) than in sunny conditions (12 hours). Assuming 8 hours of drying time per day, drying forage would require 3.5 days in cloudy conditions compared to 1.5 days in sunny conditions.

The drying hours listed in Table 22 are based on environmental conditions remaining constant with time. Since this rarely occurs, especially when the drying period extends overnight, actual drying rate varies considerably while the forage is laying in the field. The effects of management, forage moisture content, and environmental factors on drying rate can be expressed by the equation:

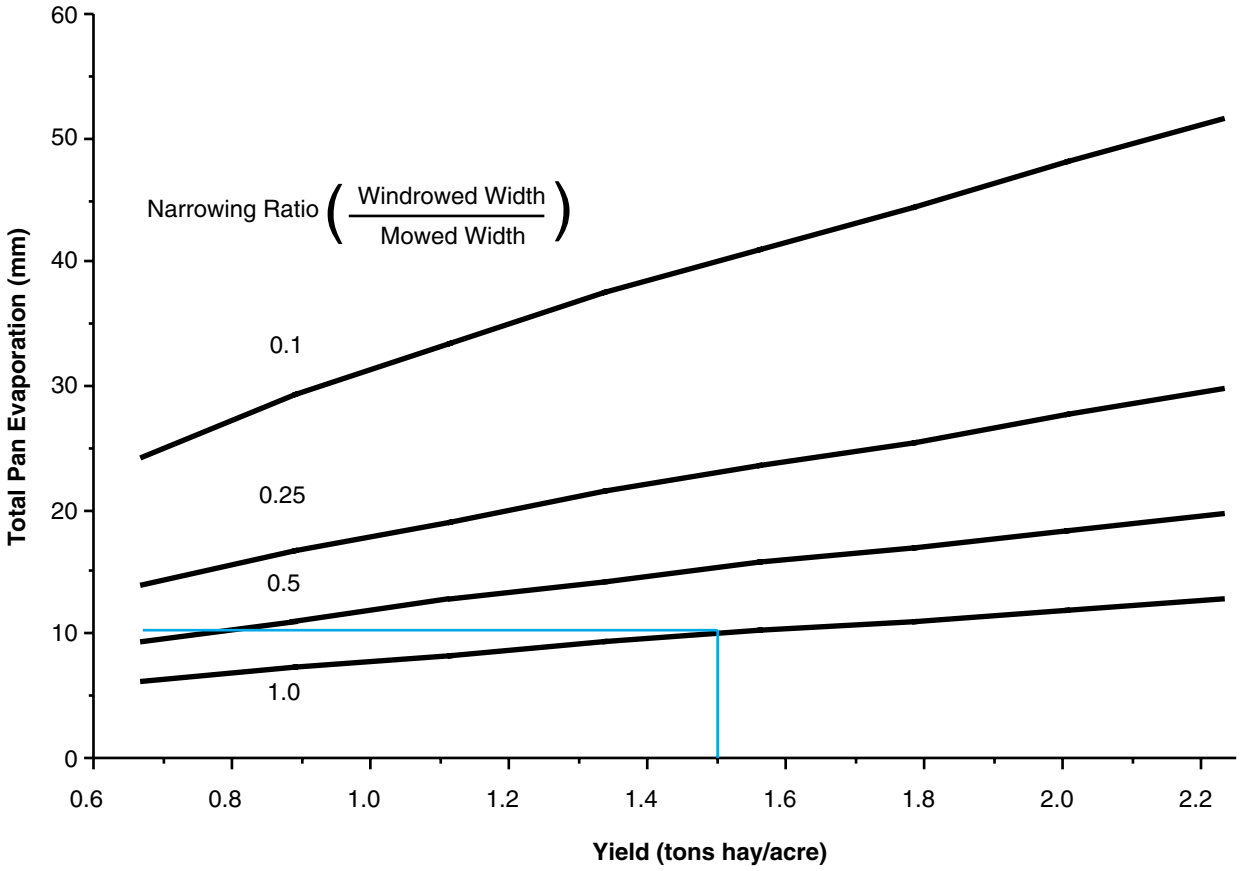
$$\left\{\begin{array}{c}\text{rate of water}\\ \text{loss from swath}\end{array}\right\} = \left\{\begin{array}{c}\text{crop/management}\\ \text{factor}\end{array}\right\} \times$$

$$\left\{\begin{array}{c}\text{available moisture}\\ \text{in forage}\end{array}\right\} \times \left\{\begin{array}{c}\text{potential}\\ \text{evaporation rate}\end{array}\right\}$$

Available moisture in the forage describes the amount of moisture remaining in the forage that can be evaporated (see Table 19, pg. 22). *Potential evaporation rate*, dictated by climate, indicates the rate at which water evaporates from an open pan in the field (*pan evaporation*). Crop species and maturity, yield, swath width, and mechanical treatment determine the *crop/management factor*. If management is poor, the hay is dry, or the air is moist, the rate of water loss is minimal.

From the above equation, it is possible to consider the *total pan evaporation* (TPE), in mm of water, needed to dry forage from as-cut moisture (80%) to baling moisture (20%). TPE is a measure of the drying potential of the environment required over the entire drying period. Figure 12 shows the TPE for alfalfa as dependent on yield at mowing and the degree to which the swath is narrowed. Narrowing the swath increases TPE because less of the forage is exposed to the surrounding environment, which reduces drying rate. For the same reason, heavier yields also increase TPE. A wide swath at mowing reduces the TPE required for drying and shortens drying time substantially.

Figure 12 Total pan evaporation (TPE) required to dry alfalfa from 80% to 20% moisture content as dependent on crop yield and on narrowing of the swath..



Source: Pitt (1985)

To calculate the average drying time in days, divide TPE (on the vertical axis of Figure 12) by the average mm of pan evaporation per day (see **Appendix D**, pg. 48). For example, the average daily pan evaporation in Ithaca, New York in July is 5.4 mm. In a full-width swath (narrowing ratio = 1.0) with a 1.5 tons of hay/acre yield, Figure 12 shows a TPE of 10 mm, so the average drying time is 10/5.4 = 1.9 days. If the swath is narrowed at mowing to half the cutterbar width (narrowing ratio = 0.5), drying time increases to 15/5.4 = 2.8 days. This demonstrates why forming a full-width swath at mowing is a recommended practice for hay-making. With a heavier yield (2 tons of hay/acre), drying times increase to 2.3 and 3.3 days for the full-width and half-width swaths, respectively. A heavy yield on first cutting coupled with a low daily pan evaporation in June are two reasons why it is difficult to make hay from first-cutting alfalfa in the Northeast.

Drying times increase if rain occurs. Some of the rain falling on the hay runs off as droplets, some is retained on the plant surfaces, and some is absorbed into the plant tissue. The absorbed moisture takes the longest to evaporate once atmospheric drying resumes.

When rain first begins, the forage retains most of the rainfall on its surfaces. As rain continues, the hay begins to "shed" the water onto the ground, especially in strong rainfalls (see Figure 13). For 1/2 inch of rainfall, the forage may be rewetted back to the moisture content at mowing. Windrowing the forage before rain restricts moisture gain, but the windrow must be raked over or inverted after the top surfaces dry off. Additional raking results in reduced forage quality and quantity.

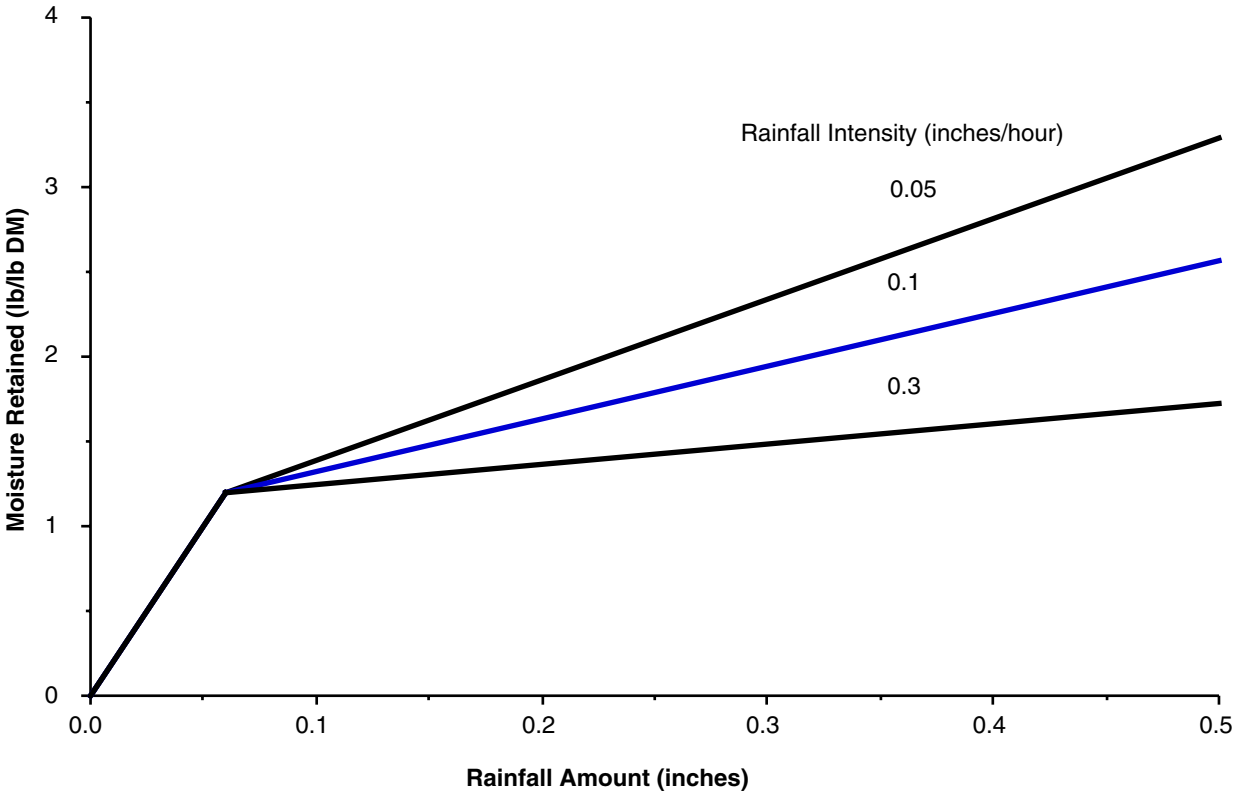
Summary

Good hay-making requires good management. Table 23 lists management practices essential for good hay-making.

Table 23 Summary of good hay-making practices.

Practices	Reasons	Benefits
Mow forage early in day.	Allow full day's drying.	Faster drop in moisture. Less respiration loss. Less likelihood of rain damage. High quantity, quality.
Form into spread swath.	Increase drying rate.	Faster drop in moisture. Less respiration loss. Less likelihood of rain damage. Higher quantity, quality.
Rake or ted at 40%–50% moisture content.	Increase drying rate.	Faster drop in moisture. Less respiration loss. Less likelihood of rain damage. Less leaf shatter. Higher quantity, quality.
Bale hay at 18%–20% moisture.	Optimize preservation.	Less leaf shatter. Inhibition of molds, browning. Low chance of fire. Higher quantity, quality.
Store hay under cover.	Protect from rain, sun.	Inhibition of molds, browning. Less loss from rain damage. Higher quantity, quality.

Figure 13 Retention of rain water by forage as dependent on the rainfall amount and intensity (rate).



Source: Pitt and McGechan (1989)

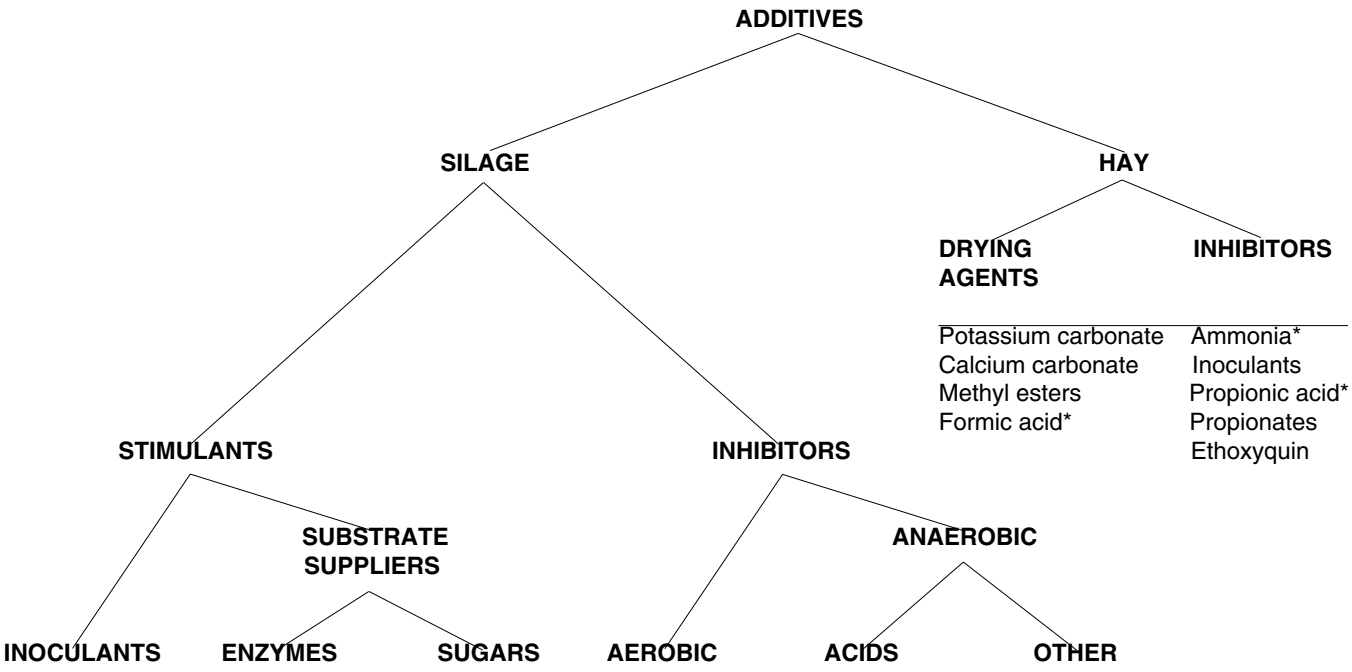
Section 3 Additives for Silage and Hay Preservation

Silage and hay additives are applied to the forage before or during placement into storage. Hay additives may enhance field drying or increase the moisture range for safe storage (see Figure 1, pg. 2). Silage additives influence the processes taking place during wilting or in the silo. Figure 14 classifies hay and silage additives according to their function. The decision to use a hay or silage additive should consider the effectiveness and cost of the additive, the need for the additive, practicality, and EPA and/or FDA label clearance.

How efficiently and accurately an additive can be applied often determines its effectiveness. The goals in applying an additive are (1) to apply the correct amount of additive per unit of forage; (2) to mix the additive thoroughly with the forage; (3) to minimize losses of the additive to the environment; (4) to minimize slowdown in the harvesting process; and (5) to prevent danger to human health.

The type of application equipment needed depends on the purpose and form of the additive. Extremely volatile

Figure 14 Organizational chart of silage and hay additives used to promote preservation.



Note: Not all of the additives listed are effective.
*There is some danger to human health associated with these additives.

Points of additive application to hay. **Table 24**

ADVANTAGES

Mowing/ Conditioning	Raking/ Tedding	Baling	Loading into Storage	After Storing
Necessary for drying agents. May restrict field losses. Conditioner helps mixing. Good control of application rate.	May restrict field losses.	Good control of application rate. Improved retention of active ingredient.	Acceptable for ammonia. Improved retention of active ingredient.	Acceptable for ammonia.

DISADVANTAGES

Mowing/ Conditioning	Raking/ Tedding	Baling	Loading into Storage	After Storing
Poor retention of active ingredient.	Poor mixing. Poor control of application rate.	No reduction of field losses.	Poor mixing. Poor control of application rate.	Poor mixing. Poor control of application rate. Often too late.

additives, such as anhydrous ammonia, are usually injected into the forage. Liquid additives require spraying equipment. Although a granular additive may prove more convenient to handle, liquid additives can be more accurately metered and result in better mixing with the forage.

The point of application in the harvesting/storing process requires careful consideration. An ideal point of application occurs when the forage passes through a "bottleneck" in the mowing/harvesting/storing processes, where the flow of additive relative to the flow of forage can be precisely controlled. Monitoring relative rates of flow of forage and additive is imperative both for applying the correct amount of additive per unit of forage and for good mixing. However, application procedures should not contribute to a greater bottleneck, compromising the benefits of additive use. Tables 24 and 25 list the advantages and disadvantages of various points of additive application in hay and silage, respectively.

Before purchasing an additive, obtain an answer to each of the following questions:

1. *What are the objectives of additive use?* Is the intent to reduce storage losses, extend the moisture range for safe storage, or preserve protein? It is important to have a specific objective in mind when selecting and using an additive (see Table 26).
2. *Does sound scientific reasoning support use of the additive?* In particular, does the additive fall under one of the functions in Figure 14, pg. 28?
3. *Is enough additive being applied to have an effect?* Application rate is one of the most critical issues in hay and silage additives. Even products with a sound scientific basis will be useless if too little is applied. A good basis of comparing different makes of an additive is the amount of active ingredient supplied per unit (e.g. lb) of forage.
4. *Is university research available to substantiate the claims made about the additive?* University evaluation through controlled, side-by-side comparisons of treated and untreated forage is currently the most credible evidence of product effectiveness. However, university results are no guarantee of success, because the conditions in a university test may not be the same as those on commercial farms.
5. *What recommendations does the manufacturer make?* The manufacturer should indicate the proper storage, handling, and application procedures to ensure the effectiveness of the additive.
6. *Can the additive be safely and properly applied?* Is technology available to meter the flow of additive onto the forage without slowing down the operation, with adequate retention of active ingredient, and most importantly, with absolute safety to human health?

Table 25 Points of additive application to silage.

ADVANTAGES

Mowing/ Conditioning (Haycrops)	Harvesting	Ensiling		After Ensiling
		Bunker	Tower	
May restrict field losses. Conditioner helps mixing. Good control of application rate.	May restrict heating in wagon/truck. Good control of application rate. Chopper helps mixing. Improved retention of active ingredient.	Avoids acid corrosion. Improved retention of active ingredient.	Avoids acid corrosion. Improved retention of active ingredient. Good control of application rate. Good mixing.	

DISADVANTAGES

Mowing/ Conditioning (Haycrops)	Harvesting	Ensiling		After Ensiling
		Bunker	Tower	
Poor retention of active ingredient. Microbials may not survive in field. Acids corrode machinery.	No reduction in field losses. Acids corrode machinery.	No reduction in field losses. Poor mixing. Poor control of application rate.	No reduction in field losses.	Poor mixing. Poor control of application rate. Often too late.

7. *Do the benefits outweigh the costs?* Economic benefit is frequently the most difficult assessment to make about an additive. Less costly products may not have the greatest overall net benefit, because they may prove ineffective. However, high cost does not guarantee product effectiveness either. For an additive meant to reduce DM losses, the value of the extra forage conserved should exceed the cost of the additive.
8. *Is the additive EPA/FDA labeled?* Legal use of an additive may require EPA or FDA approval, depending on the product type and claims made about it.

Although additives may aid in the preservation of forage, they do not compensate for inadequate management. Use of an additive should always be associated with good management. Following the practices listed in Table 17, pg. 19 and Table 23, pg. 27 will both improve preservation and increase the effectiveness of the additive.

Silage Additives

Two strategies exist for additive use in making silage. *Stimulants* enhance the growth of lactic acid bacteria and their production of organic acids which reduce pH. *Inhibitors* slow down the processes in silage; they act either selectively on undesirable processes, such as aerobic microbial growth or protein solubilization, or non-selectively on all processes. Figure 14, pg. 28 classifies silage additives according to their function.

Two types of stimulants are available for use in silage. Inoculants help the fermentation process leading to a reduced pH. Another option is to add the food (substrate) for the bacteria. *Substrate suppliers* include enzymes and sugars. *Enzyme* additives break down complex carbohydrates in the forage, such as starch, pectins, hemicellulose, or cellulose, to simple sugars for use by the lactic acid bacteria. Alternatively, the sugars can be added directly.

Silage inhibitors can be divided between those that inhibit aerobic processes and those that inhibit anaerobic processes. *Aerobic* inhibitors, such as propionic acid, suppress the growth of yeasts, molds, and aerobic bacteria. *Anaerobic* inhibitors tend to restrict undesirable bacteria (clostridia), plant enzymes (proteases), and possibly the lactic acid bacteria. *Acids* work by reducing the pH directly at the time of application. *Other* anaerobic inhibitors act primarily to protect plant proteins from solubilization.

Inoculants

Inoculants are dried or inactive microorganisms which become active when added to the forage. Inoculants are generally safe to handle and use. They usually consist of lactic acid bacteria which ferment plant sugars to lactic and acetic acids, thereby lowering the pH of the forage. Silage inoculants affect silage pH by increasing the rate of pH decline and lowering the final pH. Inoculants are usually composed of homofermentative species (see Table 6, p. 9). These bacteria produce more lactic acid as a fraction of their total end products. Thus the lactic acid content of inoculated silage should be higher and the final pH lower (see Table 27). Also, by increasing the initial number of lactic acid bacteria on the forage, the inoculant gives fermentation an earlier start and the pH should be lowered more rapidly. This aids the basic objective of a rapid and extensive decrease in pH in silage preservation.

Inoculants may have the following benefits:

- ☐ Reduced silo temperatures (see Table 27).
- ☐ Reduced DM and energy losses in storage.

Key to silage and hay additives. **Table 26**

Goal of additive use	See these sections.[a]	Page: Silage	Page: Hay
Reduce field losses during drying and harvesting.	Propionates	36	39
	Drying agents	41	41
	Formic acid/formaldehyde	37	
Bale hay at moisture content above 20%.	Inoculants		41
	Propionates		39
	Ammonia/urea		40
Reduce in-silo losses.	Inoculants	31	
	Sugars	34	
	Enzymes	34	
	Propionates	36	
	Formic acid/formaldehyde	37	
Reduce silage pH.	Inoculants	31	
	Sugars	34	
	Enzymes	34	
	Formic acid/formaldehyde	37	
Decrease soluble protein levels.	Inoculants	31	
	Sugars	34	
	Enzymes	34	
	Propionates	36	
	Ammonia/urea	37	
	Formic acid/formaldehyde	37	
Increase silage bunk life.	Inoculants	31	
	Propionates	36	
	Ammonia/urea	37	
	Formic acid/formaldehyde	37	

[a]Mention of an additive with a desired goal does not necessarily mean that the additive will achieve that goal.

☐ Increased bunk life (see Table 27).
☐ Reduced protein solubilization.

Table 28 compares losses and chemical composition of untreated alfalfa silage and alfalfa silage inoculated with lactic acid bacteria. For forage ensiled on Day 1 of the experiment, no benefit from inoculation occurred. For forage ensiled on Day 2 of the experiment, final pH and soluble protein levels were lower in the inoculated silage.

Silage inoculants do not always show a significant positive effect on pH or DM losses (see Table 28). Also, their effect on the rate of fermentation early in the ensiling process appears insufficient to inhibit protein solubilization to any great extent (see Table 29). The effectiveness of inoculation in silage fermentation depends on several factors:

1. *Viability*. Fermentation involves living organisms. The inoculated bacteria must be capable of growing in the forage. Inoculation with dead bacteria has no effect.
2. *Shelf life*. The inoculant should be stored in a cool location for no longer than is recommended by the manufacturer. Storage in hot environments may render the inoculant useless.
3. *Forage moisture content*. Like all lactic acid bacteria, inoculants will most likely dominate the fermentation at 30%–50% DM content.
4. *Sufficient plant sugars*. Bacterial growth requires sugars. The effect of the inoculant is limited if there are insufficient plant sugars for maximum fermentation to the lowest possible pH (see Table 7, pg. 10 for the sugar requirements for maximum pH reduction and Table 8, pg. 11 for the factors affecting sugar content before fermentation).
5. *Proper application*. Uniform distribution of the inoculant in the forage is critical for promoting bacterial access to plant sugars. The best point of application for inoculants is at chopping (or at ensiling in tower silos). Liquid forms are preferable to granular forms.
6. *Appropriate species of bacteria*. Inoculants consisting of homofermentative lactic acid bacteria are most successful in affecting the rate and extent of

Table 27 Effect of inoculation on corn silage.

	Untreated	Inoculated with 100,000 lactic acid bacteria/gram forage
DM content (%)	33	38
CP (% DM)	8.2	8.4
pH	4.22	4.09
Mold count (per gram)	4×10^6	2×10^5
Yeast count (per gram)	3×10^7	5×10^7
Temperature at unloading (°F)	82	74

Source: Wohlt (1989)

Table 28 Losses and chemical composition of untreated alfalfa silage and alfalfa silage inoculated with lactic acid bacteria.

	Forage ensiled on Day 1			Forage ensiled on Day 2		
	Untreated	Inoculated	Significance	Untreated	Inoculated	Significance
DM content (%)	30.5	31.9	NS	47.1	40.6	S
DM losses (%)	19.0	22.9	S	7.6	12.0	S
Gross energy (kcal/gram)	4.5	4.5	NS	4.3	4.4	S
pH	4.7	4.7	NS	4.8	4.6	S
Crude protein (% DM)	18.2	17.5	NS	18.2	17.7	NS
Soluble protein (% CP)	67.3	66.3	NS	68.5	66.0	S

NS = not statistically different at the 5% level.
S = statistically different at the 5% level.

Source: Pitt et al. (1985a)

Effect of inoculation on soluble protein (SP) content of alfalfa and grass silages. **Table 29**

Forage	DM content (%)	Soluble protein (% CP)		
		Before ensiling	Untreated	Inoculated at 10^6 cfu/gram[a]
Alfalfa	44	39	71	69
Grass	44	36	59	56
	20	36	62	59

[a]cfu/gram forage = number of colony-forming units added per gram of fresh forage.

Source: Pitt and Leibensperger (1987)

Wilting conditions under which a properly applied silage inoculant consisting of lactic acid bacteria is likely to be effective. **Table 30**

Given Wilting time (hours)	and Temperatures during wilting	and Addition level, cfu/gram forage			
		10^3	10^4	10^5	10^6
		the DM content at harvest should be below 60 % and **above**			
24	**Cool**	NE	35%	25%	25%
	Warm	NE	40%	30%	25%
48	**Cool**	NE	50%	40%	25%
	Warm	NE	NE	50%	40%
72	**Very cool**	NE	50%	45%	35%
	Cool	NE	NE	50%	35%

"NE" means "not effective."
"Very cool" means average temperatures of 59°F–66°F.
"Cool" means average temperatures of 66°F–72°F.
"Warm" means average temperatures of 72°F–77°F.

pH decline in silage. Compare the product's label to the list of scientific names in Table 6, pg.9. Inoculation with yeasts may promote the wrong type of fermentation and may decrease aerobic stability.

7. *Sufficiently high addition levels.* Addition level of inoculants is usually expressed as the number of colony-forming units added per gram of fresh forage (cfu/gram forage). One cfu/gram forage indicates that, on average, at least one viable microbe has been added to each gram of forage. Addition level is the most important measure of an inoculant's quality.

For an inoculant to have an effect, more bacteria must be added than exist on the forage at ensiling. Based on Table 9, pg. 12, Table 30 was developed to project the conditions in which an inoculant is likely to be effective. Factors which aid inoculant effectiveness include shorter wilting times, cooler temperatures, drier forage, and especially addition level.

For example, if alfalfa is wilted for 48 hours in cool conditions and treated with an inoculant adding 10^5 cfu/gram forage, Table 30 shows that the DM content at harvest for alfalfa under these conditions must exceed 40% for the inoculant to be effective. As another example, suppose alfalfa is ensiled at 25% DM content in a bunker silo after wilting for 24 hours under warm conditions. Table 30 indicates that an inoculant must supply at least 10^6 (1,000,000) cfu/gram forage to be successful in this case.

In general, the more cfu/gram added by an inoculant, the more likely it is to be effective. Only inoculants which provide at least 100,000 (10^5) cfu/gram forage are recommended (see Table 31).

In summary, an inoculant for silage should: (1) have guaranteed viability, (2) be applied as a liquid, (3)

contain primarily homofermentative lactic acid bacteria (see Table 6, pg. 9), (4) supply at least 100,000 cfu/gram forage, and (5) be university tested.

Sugars

Sugars are the substrate for lactic acid fermentation in silage, and sufficient quantities are required for a rapid and extensive decline in pH in the silo. Sugar additives are safe to handle and apply and include molasses (mostly sucrose), glucose, dextrose, corn derivatives, and rice by-products. Legumes of less than 35% DM content and unwilted grasses do not normally contain sufficient sugars for maximum fermentation (see Table 7, pg. 10). If sugars are depleted during fermentation, pH will stop at an unfavorably high level, resulting in incomplete fermentation. Adding sugars to the forage (one type of substrate supplier) before ensiling promotes maximum fermentation to the lowest possible pH.

Addition of sugars to crops which already have sufficient sugars for maximum fermentation increases the residual sugar content at the end of ensiling, but total sugars used during fermentation, lactic acid production, and final silage pH remain unaffected. Increasing the addition level does not improve preservation in this case and may reduce bunk life. Sugar addition to haycrop silage wilted to at least 35% DM or to corn silage does little to improve preservation.

Addition of sugars to crops with insufficient sugars for maximum fermentation (alfalfa with DM content below 35%) extends the fermentation process, increases lactic acid production, and reduces final pH. Sugar addition may also result in a greater proportion of lactic acid among the acids produced during fermentation. Factors associated with these effects may include reduced DM losses in storage, increased bunk life, and less likelihood of clostridial spoilage in forages of DM content less than 30%.

The need for sugar addition to a particular silage crop depends on the sugar content of the forage at ensiling. Although the factors affecting initial sugar content are known (see Table 8, pg. 11), and the sugar requirements for maximum fermentation can be projected (see Table 7, pg. 10), routine measurements of sugar content at ensiling are not made. For this reason the need for sugar addition is uncertain.

Even when sugar additives affect final silage pH, they have little effect on protein solubilization (see Table 32), because sugar additives affect pH only when the plant sugars would otherwise be depleted, i.e. late in the ensiling process. However, most protein solubilization occurs in the first 7 days of storage in the silo; sugar additives do not greatly affect pH within this time.

Enzymes

Enzyme additives for silage (a second type of substrate supplier) consist of proteins that speed up certain biochemical reactions in silage. Most enzyme additives break down complex carbohydrates to simple sugars that can be used in the fermentation process. They are similar to sugar additives in their effect on silage. However, to affect fermentation, the enzymes must act rapidly enough to release sugars before the end of fermentation.

There are several types of enzymes available for use in silage.

1. *Hemicellulases* break down hemicellulose to 5-carbon sugars (pentoses) which can be used in fermentation. Breakdown of hemicellulose reduces NDF content.

Table 31 Likelihood of inoculant effectiveness in silage as dependent on cfu added/gram forage.

Addition level (cfu/gram forage)		% of time the inoculant will work
100	(10^2)	15
1,000	(10^3)	25
10,000	(10^4)	45
100,000	(10^5)[a]	70
1,000,000	(10^6)	85
10,000,000	(10^7)	95

[a]Recommended minimum level.

Source: Pitt and Leibensperger (1987)

Effect of sugar (molasses) addition to alfalfa and grass silages.

Table 32

Crop	DM content (%)	Molasses added (% DM)	Final pH	Residual sugars (% DM)	Lactic acid (% DM)	Crude protein (% DM)	Soluble protein (% CP)
Alfalfa	17	0	5.4 (c)	0	0	27	61.4
		12	4.9	0	1.2	27	60.8
		24	4.2	0	5.9	27	60.5
	30	0	4.8	0.1	2.4	27	57.3
		12	4.4	0.1	4.6	27	57.3
		24	4.6	6.6	3.8	27	57.4
	45	0	4.8	0.1	2.4	27	50.0
		12	4.9	4.4	2.3	27	50.1
		24	4.9	9.3	2.2	27	50.1
Grass	17	0	4.0	0.3	6.4	14	52.1
		12	3.8	1.7	8.5	14	52.1
		24	3.8	9.2	8.3	14	52.1
	30	0	4.2	10.8	4.3	14	51.3
		12	4.2	17.2	3.8	14	51.4
		24	4.3	23.5	3.5	14	51.5
	45	0	4.9	16.7	1.3	14	45.1
		12	4.9	22.4	1.3	14	45.2
		24	4.9	27.2	1.3	14	45.3

(c) = clostridial silage

Source: Leibensperger and Pitt (1988)

2. *Cellulases* break down cellulose to glucose for use during fermentation. Breakdown of cellulose reduces NDF and ADF contents.
3. *Amylases* break down starch to sugars useful in fermentation. Legumes contain substantial quantities of starch; grasses do not.
4. *Pectinases* break down pectins to sugars that can be used during fermentation.
5. *Proteases* break down plant proteins to a soluble non-protein form. Since protein solubilization is an undesirable process in silage, proteases are undesirable as a silage additive.

All the enzymes except proteases, which irritate skin, are safe to handle. The reduction of NDF and ADF by hemicellulases and cellulases potentially increases silage intake and digestibility. However, the enzymes may act on the most digestible fraction of NDF and ADF, so that animal response may be less than would be expected from the apparent changes in fiber concentrations. Also, NE_L predictions from ADF content of enzyme-treated silages may be erroneously high. Table 33 shows the results of a study in which cellulase addition to three crops reduced cellulose content but had no consistent effect on final pH.

Speed of action is critical to the effectiveness of an enzyme additive for silage. Factors affecting the rate of enzyme activity include:
1. *Enzyme addition level*. Higher addition levels increase the rate at which cellulose, hemicellulose, and starch are broken down in the silo. Addition level is the principal factor governing the effectiveness of an enzyme additive.
2. *Temperature*. Higher silo temperatures increase the rate of enzyme activity. But silo temperatures above 95°F cause cellulases to deteriorate, limiting the length of time the enzyme remains active and decreasing its effectiveness in silage (see Table 33). Management practices which limit silo temperatures will enhance the effectiveness of the enzymes.
3. *pH*. The pH for maximum enzyme activity depends on the type and source of the enzyme. Cellulase activity is typically highest at pH 4.5, which is ideal for a silage additive. Amylase activity is highest at pH 6.0. Some amylases deteriorate rapidly at pH below 4.0.

Table 33 Effect of cellulase addition (2.2 lb/ton) on final pH and cellulose reduction in grass silage after 280 days of storage.[a]

Crop	DM content (%)	Temperature (°F)	Final pH		Cellulose reduction (%)[b]	
			untreated	treated	untreated	treated
Alfalfa	11	32	4.21	4.28	1.9	6.5
		59	4.03	4.06	-3.2	14.0
		95	4.18	4.08	3.7	18.1
		122	4.32	4.28	-4.2	8.8
Red clover	23	32	4.35	4.38	-6.9	3.3
		59	4.29	4.13	2.4	0.4
		95	4.21	4.19	15.0	0.4
		122	4.33	4.27	-8.5	1.2
Ryegrass	17	32	4.08	4.22	11.7	28.6
		59	4.12	4.13	9.9	45.1
		95	4.15	4.23	9.9	45.1
		122	4.26	4.14	6.6	13.6

[a]These silages were made in laboratory-scale silos under European conditions (note very low DM contents).
[b]A negative value means cellulose concentration increased during storage.

Source: Henderson et al. (1982)

Table 34 Effect of propionic acid addition at 1 lb/ton DM to 38% DM alfalfa silage.

	Untreated	Treated
DM loss (%)	15	8
Crude protein loss (%)	18	13
Gross energy loss (%)	13	5
Mean temperature (°F)	94	86

Source: Chase et al. (1982)

4. *DM content*. Enzyme activity decreases as DM content increases, and ceases at approximately 80% DM, the moisture level of baled hay.
5. *Time in silo*. Cellulases and hemicellulases do not act instantaneously. The silage should be stored for at least 90 days to obtain maximum reductions of NDF and ADF.

Propionates

Propionates minimize aerobic activity in silage-making. When applied at mowing, propionates limit plant respiration during drying (see **Propionates**, pg. 39); however, much of the additive is lost through evaporation. When applied at chopping, the propionates restrict heating of the forage in the wagon or truck. In the silo, propionates reduce the DM and energy losses associated with the infiltration of oxygen, by lowering the activity of yeasts, molds, aerobic bacteria, and plant respiration. Propionates also reduce silo temperatures (see Table 34), which in turn reduces protein solubilization and heat damage and increases bunk life (see Table 35). Spraying propionates on the outer surfaces of the silage in bunker silos reduces aerobic deterioration.

Propionic acid is caustic to skin and eyes and corrosive to farm equipment. It must be handled and stored carefully. Precautions include wearing protective clothing such as eye and face protection, long sleeves, gloves, long trousers, and work boots. Buffered propionates are safer to handle and are similar in effect to propionic acid.

Ammonia/Urea

When added to forage, ammonia or urea increases crude protein and soluble protein contents. Ammonia also has anti-bacterial properties and can act as a preservative. *Breathing ammonia vapors quickly damages lung tissue and must be avoided. Ammonia may also cause eye burns and freeze burns.*

Ammonia addition to silage is most often associated with corn crops, because of their low CP content and high level of fermentable carbohydrates. Ammonia is strongly alkaline and tends initially to raise the pH of the forage. It may then stimulate growth of the lactic acid bacteria, although the final pH still tends to be higher than without ammonia because of the increased buffering of the additive. Anhydrous ammonia rapidly combines with the water in the forage and may release some heat as it goes into solution. Urea acts somewhat like ammonia but is not as effective; naturally-occurring urease enzymes break down urea to ammonia and carbon dioxide, but the breakdown rate may be too slow to create a strong ammonia environment.

Although addition of ammonia increases the CP and SP fractions of silage, it also limits, to some extent, protein solubilization. The true (non-soluble) protein content as a % of DM can be increased slightly by ammonia addition (see Table 36). Ammonia can also increase bunk life of corn silage by killing the yeasts and molds responsible for aerobic deterioration or by increasing lactic acid content, which inhibits growth of yeasts and molds. However, as shown in Table 37, if the addition level is too high, ammonia or urea will suppress fermentation, decrease bunk life, and reduce feed intake.

Formic Acid/Formaldehyde

Formic acid is commonly used in Europe in mixtures with formaldehyde as a silage additive for direct-cut forages. Formic acid is a strong acid which acts by immediately reducing the pH of the forage to restrict biochemical activity. In this manner, formic acid prevents clostridial spoilage in forages below 30% DM content and works effectively to inhibit protein solubilization at any DM level.

Percentage DM losses from aerobic deterioration of corn silage exposed to air for 19 days at 60°F, with and without propionic acid treatment.

Table 35

Application rate (lb/ton DM)	DM content (%)		
	20	28	34
0	18	19	20
25	10	3	0
50	6	0	0

Source: Woolford and Cook (1977)

Effect of urea addition at 12 lb/ton on fermentation of 30% DM corn silage.

Table 36

Time in silo (days)	pH		Crude protein (% DM)		True protein (% DM)		Ammonia (% CP)		Lactic acid (% DM)	
	u	t	u	t	u	t	u	t	u	t
0	5.9	5.9	8.9	[14.5]	5.0	[5.0]	0.5	[10.6]	0	0
2	3.9	3.6	8.1	19.5	3.7	3.9	1.0	2.6	1.7	2.8
5	3.4	3.5	10.9	18.2	4.2	5.9	0.8	3.1	2.7	4.5
10	3.4	3.5	9.2	19.0	4.3	5.5	0.7	2.7	10.0	5.3
15	3.2	3.5	9.3	18.2	4.0	4.7	0.8	3.2	6.2	7.0
20	3.2	3.6	8.4	20.7	3.7	5.1	0.9	3.5	8.5	15.5

"u" = untreated.
"t" = treated.
[ ] = considered unreliable because of sampling problems.

Source: Lessard et al. (1978)

Formic acid is extremely dangerous to handle. The additive is caustic to skin and eyes and corrosive to farm equipment. Formic acid is also volatile, and its fumes can be extremely damaging to skin, eyes, lungs, and nasal passages. Formic acid should never be used without breathing masks and protective clothing for all skin surfaces. Although European systems for storing, handling, and applying the acid minimize these dangers, those technologies are not currently available in the U.S. Formic acid application to low-DM forages also increases the flow of effluent, increasing the nutrient losses and farmstead pollution. Also, formic-acid treated silages tend to be aerobically unstable.

By immediately reducing forage pH before ensiling, formic acid inhibits protein solubilization when the plant proteases are most active. Table 38 shows that more formic acid must be applied to legumes than to grasses to induce the same effect, because the higher buffering of the legumes reduces the impact of the acid on forage pH. An addition rate of 1% of forage DM requires more acid per ton of treated forage when the DM content of the forage is higher (see Table 38).

Table 37 Effect of urea and ammonia addition to 35% DM corn silage.

	Addition level (lb/ton)	pH	Lactic acid (% DM)	Maximum temperature during fermentation (°F)	Days to visible mold growth in air
Untreated	0	4.13	5.8	90	4
Urea	10	4.35	5.7	90	11
	20	4.50	5.4	96	12
	40	5.53	7.7	90	4
Ammonia	20	4.33	7.1	—	—
	40	4.88	4.3	—	—
	80	6.60	0.6	—	—

Source: Britt and Huber (1975)

Table 38 Effect of formic acid addition on pH and soluble protein levels in silage.

DM content (%)	Addition level		pH after addition		Final pH		Soluble protein (% CP)	
	% of DM	lb/ton[a]	alfalfa	grass	alfalfa	grass	alfalfa	grass
17	0	0	6.3	6.1	5.4[b]	4.0	61	52
	0.5	1.7	5.6	5.2	4.6	3.9	56	42
	1.0	3.4	5.1	4.6	4.4	4.0	48	33
	2.0	6.8	4.5	—	4.2	—	39	—
30	0	0	6.3	6.1	4.8	4.2	57	51
	0.5	3.0	5.6	5.2	4.6	4.4	53	40
	1.0	6.0	5.1	4.6	4.9	4.8	45	32
45	0	0	6.3	6.1	4.8	4.9	50	45
	0.5	4.5	5.6	5.2	5.1	5.3	46	35
	1.0	9.0	5.1	4.6	5.2	4.8	40	29

[a]lb per ton of wet silage
[b]clostridial silage

Source: Leibensperger and Pitt (1988)

Effect of formaldehyde addition on 18% DM ryegrass silage. **Table 39**

Addition level (gal/ton)	pH	Lactic acid (% DM)	Ammonia–N (% total N)	DM digestibility in sheep (%)	DM intake in sheep (% of 0 addition)
0	4.2	11	7	80	100
0.7	4.6	9	8	77	93
1.2	5.1	10	5	73	94
1.9	5.4	2	2	75	95
3.0	5.4	1	2	65	40
4.1	5.3	1	1	60	23

Source: Wilkins et al. (1974)

Effect of formic acid/formaldehyde combinations on 20% DM ryegrass/clover silage. **Table 40**

	Untreated	Formalin	Formalin & formic acid
Addition level (gal/ton)	0	1.2	1.4
pH	4.6	4.7	4.5
Crude protein (% DM)	15	15	14
Soluble protein (% CP)	53	29	19
Ammonia-N (% total N)	16	9	6
Lactic acid (% DM)	3	2	2
DM digestibility in sheep (%)	64	63	62

Source: Barry (1975)

Formaldehyde (sold commercially as a solution called formalin) exhibits strong anti-microbial properties in silage and can protect plant proteins from solubilization. *Formaldehyde is a suspected carcinogen, and any contact with the material should be avoided.* Check FDA regulations concerning the legality of formaldehyde use before purchasing.

At low application levels (less than 2 gal/ton), formaldehyde decreases soluble protein levels in silage without detrimentally affecting the fermentation process. However, formaldehyde may decrease bunk life. At higher application levels, formaldehyde inhibits lactic acid bacteria and results in incomplete preservation. Also, at high addition levels the plant proteins protected by the formaldehyde may become indigestible to the ruminant, and the overall DM digestibility may decrease (see Table 39). Feed intake can also be reduced if the formaldehyde disrupts the microbial populations in the rumen.

Formic acid and formaldehyde are compatible as silage additives, and in Great Britain the two additives are frequently combined. Together, they restrict protein solubilization, and because each of the additives can be used in lower amounts, the problems associated with feeding high levels of formaldehyde are mitigated (see Table 40).

Hay Additives

Two strategies exist for additive use in making hay. *Drying agents* speed the drying process in the field, but the optimum moisture content for storage is still 18%-20%. *Inhibitors* restrict aerobic processes to make safe storage of hay possible above 20% moisture; this reduces leaf loss during baling and the possibility of rain damage (see Table 21, pg. 24). Figure 14, pg. 28, classifies hay additives according to their function.

Propionates

Propionic acid (C_2H_5-COOH) is an organic acid which inhibits aerobic activity in hay and permits safe storage at moisture contents greater than 20%. Propionates act by disrupting the enzymatic processes associated with plant and microbial respiration. The principal factor in their effectiveness is addition level. Buffered propionates evaporate less and can be applied at slightly lower levels.

Table 41 shows the effect of propionate application rate on molding and heating in hay. At 20 lb/ton hay, propionic acid is generally effective in preventing mold development and heating (see Table 42). However, uneven application may result in the presence of some mold. The acid has little benefit for hay below 20% moisture (see Table 43). Good mixing is required for propionates to function effectively.

Propionic acid is dangerous to skin and eyes, and corrosive to farm equipment. It must be handled and stored carefully. Precautions include wearing protective clothing such as eye and face protection, long sleeves, gloves, long trousers, and work boots. Buffered propionates are safer to handle.

Ammonia/Urea

Ammonia treatment permits safe storage of hay at moisture contents greater than 20%. The ammonia prevents mold growth and keeps temperatures at safe levels. More ammonia must be added as the moisture content of the forage increases. Ammonia treatment is

Table 41 Effect of propionate application rate on storage of alfalfa hay.

Treatment	Addition level (lb/ton hay)	Moisture content (%)	Visual mold score (0–4)	Maximum bale temp. (°F)	DM losses over 36 days (%)
None	0	23	2.9	111	
Sodium propionate	5	23	2.9	109	
	10	24	3.1	111	
	15	21	2.8	111	
Propionic-acetic	10	22	2.8	106	
	15	23	2.2	97	
None	0	24	1.7	120	
Propionic-acetic	15	25	0.8	108	
None	0	21	2.5	109	
Propionic-acetic	10	21	1.0	100	
None	0	26		116	9.9
Propionic-acetic	45	30		84	4.5

Source: Walgenbach (1988)

Table 42 Effect of propionic acid applied at 20 lb/ton hay on molding of alfalfa hay at varying moisture levels.[a]

	Moisture content (%)	Time after treatment (days)		
		6	28	45
Untreated	20	0	1	3
Treated	20	0	0	0
Untreated	25	2	8	9
Treated	25	0	0	0
Untreated	30	3	10	10
Treated	30	0	0	0

[a]Numbers given are visual mold score (0 = no molding, 10 = maximum molding).

Source: Rotz et al. (1988)

Effect of propionic acid at 20 lb/ton on quality of alfalfa hay stored for 45 days.

Table 43

	Moisture content (%)	Temperature (°F) maximum	Temperature (°F) mean	DM loss (%)	Crude protein (% DM)	ADIP (% DM)	ADF (% DM)	Mold Score (1–10)
Untreated	17	69	64	0	16	1.3	41	3
Treated	18	69	64	3	17	1.3	42	5
Untreated	19	70	65	3	20	1.0	28	3
Treated	20	81	63	3	21	1.1	26	3
Untreated	23	103	88	7	24	1.3	27	5
Treated	24	81	63	2	20	1.3	29	3

Source: Rotz et al. (1988)

Effect of ammonia addition at 50 lb/ton on alfalfa hay after 30 days storage.

Table 44

	Moisture content (%)	Temperature (°F) maximum	Temperature (°F) mean	DM loss (%)	Crude protein (% DM)	ADIP (% DM)	ADF (% DM)	Mold Score (0–10)
Untreated	23	117	90	5	17	1.0	36	5
Treated-open	21	99	79	3	19	1.2	33	2
Treated-wrapped	22	102	86	1	19	1.3	34	2
Untreated	28	113	90	7	19	1.2	29	4
Treated-open	23	93	79	5	19	1.4	36	1
Treated-wrapped	22	82	75	0	23	1.3	32	0
Untreated	31	111	97	9	19	1.0	25	2
Treated-open	31	90	88	8	22	1.3	28	2
Treated-wrapped	31	99	86	0	22	1.2	25	4
Untreated	41	131	102	5	15	1.6	40	9
Treated-open	40	135	108	8	18	1.7	38	8

Source: Rotz et al. (1986)

more effective when the bales are covered, wrapped or bagged after injection (see Table 44); otherwise, ammonia will be lost through evaporation. Ammonia addition to high-protein hay may cause toxicity problems. A more in-depth discussion of ammonia/urea, including handling precautions, can be found in **Ammonia/Urea**, pg. 37.

Inoculants

Hay inoculants are microorganisms intended to preserve hay at high moisture content. *However, inoculation of hay with anaerobic bacteria has not been shown to permit safe storage at moisture contents between 20% and 40%* (see Table 45). Lactic acid bacteria cannot grow at moisture contents less than 35% (see Figure 1, pg. 2), and hay is highly aerated and therefore cannot undergo fermentation, which requires anaerobic conditions. In general, fermentation is not a proper strategy in the preservation of hay (see **Introduction**, pg. 1). Hence, the use of inoculants at moisture contents below 40% is of no benefit for hay preservation.

Drying Agents

Drying agents for hay are water-based solutions that are sprayed on the crop at mowing to encourage faster drying. They usually consist of potassium carbonate (K_2CO_3) and/or sodium carbonate (Na_2CO_3) and a surfactant to help spreading. They are not highly corrosive and are relatively safe to handle. Drying

agents act by disturbing the waxy cuticle on the outside of the stem, reducing resistance to water loss from the plant during drying.

The factors that determine field drying rates (see **Factors Affecting Field Drying Rates**, pg. 24) are the same with or without drying agents. The following equation, explained on p. 25, emphasizes that crop/management factors, forage moisture content, and environment affect drying rate.

$$\left\{\begin{array}{c}\text{rate of water}\\ \text{loss from swath}\end{array}\right\} = \left\{\begin{array}{c}\text{new crop/}\\ \text{management factor}\end{array}\right\} \times \left\{\begin{array}{c}\text{available moisture}\\ \text{in forage}\end{array}\right\} \times \left\{\begin{array}{c}\text{potential}\\ \text{evaporation rate}\end{array}\right\}$$

(increased by drying agents)

The crop/management factor is increased by drying agents, so for the same available moisture and climatic conditions, the rate of water loss from the swath is increased. However, the drying rate remains zero if the forage is already dry (available moisture at zero) or if climatic conditions are unfavorable (potential evaporation at zero). Drying agents make the crop more susceptible to the drying power of the environment as determined by temperature, relative humidity, wind speed, solar radiation, and soil moisture; they have the greatest impact on crops when drying conditions are good.

Because drying agents increase the crop/management factor in determining rate of water loss from the swath, the total pan evaporation (TPE) needed to reach baling moisture is reduced (see Table 46). On average, if the crop is mowed early on the 1st day, baling occurs on the 3rd day with no drying agent and late on the 2nd day with a drying agent.

The following restrictions apply to the effective use of a drying agent:

Table 45 Effect of inoculation on molding of alfalfa hay.

Moisture content (%)	Inoculation	Mold score, day 45 (0 = none, 10 = high)
12	none	0
20	none	3
20	1-2 x 10^5 lactic acid bacteria/g	3 – 4
20	1-2 x 10^5 propionic acid bacteria/g	3 – 5
25	none	9
25	1-2 x 10^5 lactic acid bacteria/g	10
25	1-2 x 10^5 propionic acid bacteria/g	7 – 9
30	none	10
30	1-2 x 10^5 lactic acid bacteria/g	10
30	1-2 x 10^5 propionic acid bacteria/g	10

Source: Rotz et al. (1988)

Table 46 An example of the effect of drying agents on drying time to reach baling moisture.

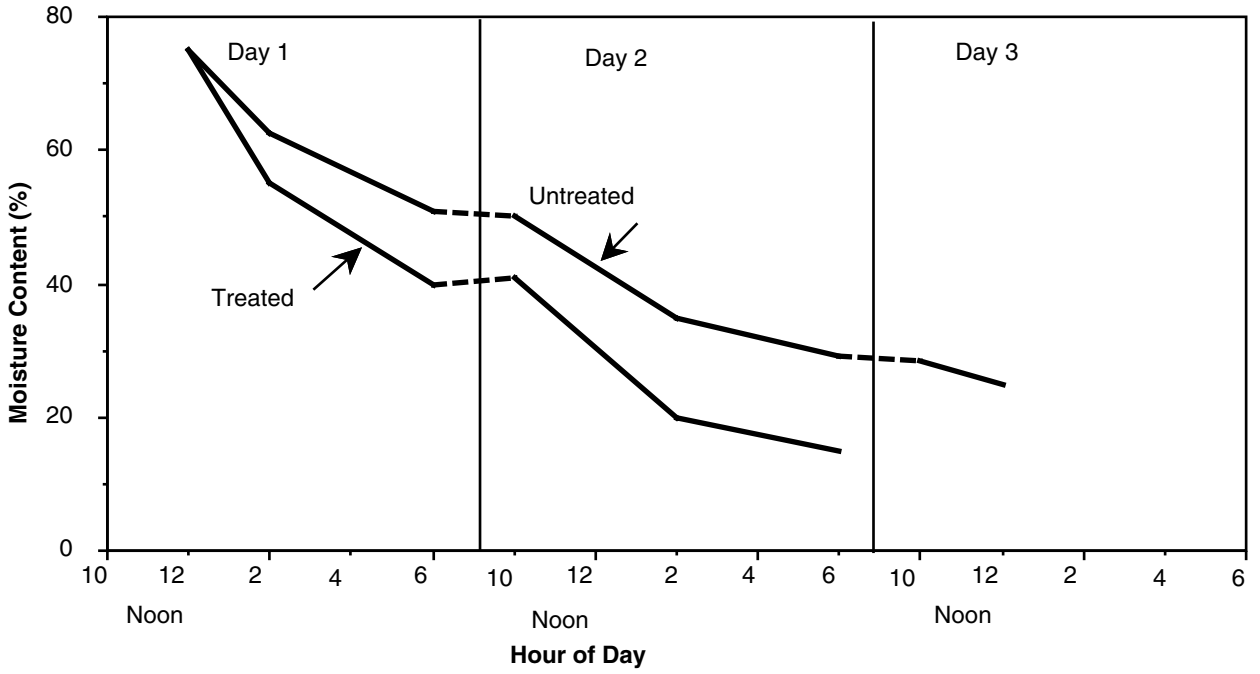
	TPE (mm)	÷	Average pan evaporation (mm/day)	=	Average days to dry hay
Untreated	16	÷	5.4	=	2.9
Treated	10	÷	5.4	=	1.9

Note: See Appendix D for average pan evaporations at various locations.

Source: Pitt (1985)

Moisture content of alfalfa versus time in the field for untreated forage and for forage sprayed with a drying agent at mowing.

Figure 15



Source: Pitt (1984)

Effect of drying agents on quality of stored alfalfa hay.

Table 47

	Untreated	Treated
Moisture content (%)	14	14
Crude protein (%DM)	18.5	18.8
ADF (% DM)	30.8	30.1
NDF (% DM)	38.8	36.8
In vitro DM digestibility (%)	57.8	62.5

Source: Oellermann et al. (1989)

1. *Legumes only*. Drying agents have their greatest effect on alfalfa and birdsfoot trefoil. They are less effective on red clover and are ineffective on grasses. In a mixed stand of 50:50 alfalfa/grass, they will exhibit less of an effect than on alfalfa alone.
2. *Later cuttings*. Drying agents work best on 2nd, 3rd and Fall cuttings. They are less effective on 1st cutting when yields are heavy and the climate is less favorable for drying.
3. *Hay only*. For silage wilting, the cost and inconvenience of drying agents outweigh the benefits.
4. *Bale at 18%-20% moisture*. Drying agents do *not* permit safe storage of hay at moisture contents above 20%.
5. *Wide swath*. Drying agents are more effective when the crop is formed into a full-width swath at mowing. This more fully exploits the drying power of the environment.
6. *Uniform spreading*. Even distribution of the drying agent solution onto the crop surfaces, especially the stems, is critical. The drying agents should be sprayed ahead of the cutterbar or conditioning rolls to help spread the solution over the crop surfaces.
7. *Less concentrated solutions*. Because water improves distribution of the drying agent, applications of 50 gallons/acre are more effective than 30 gallons/acre when the same amount of drying agent is applied. In practice, the volume of water applied per acre is limited by the carrying capacity of the tanks.

Under the above restrictions, drying agents will on average make baling possible late on the 2nd day after mowing rather than on the 3rd day (see Figure 15). With faster drying in the field, the drying agents offer the following benefits:

1. *Reduced respiration loss*. Plant respiration is inhibited as moisture content decreases during drying. Faster drying reduces the nutrient and energy losses associated with respiration.

2. *Reduced environmental exposure*. With faster drying, less rain damage and fewer nutrient and energy losses are likely to occur.

On average, drying agents can be expected to reduce DM losses by 75 lb/acre and crude protein losses by 30 lb/acre. This results in more available nutrients per acre and better feed utilization by the animal (see Table 47).

Approximate Dry Matter Capacities of Tower Silos (tons)[a]

Appendix A

Silo height (ft)	Silo diameter (ft)										
	10	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
20	8	12	16	21	27	33	40	47	56	65	74
24	11	15	21	27	34	43	52	61	72	83	96
28	13	19	26	35	44	53	64	76	90	104	119
32	16	23	32	41	52	65	78	93	109	127	145
36	19	28	37	48	62	76	92	109	129	150	172
40	22	32	44	57	72	89	107	127	150	173	199
44		37	50	65	82	102	123	147	172	200	229
48		42	56	74	93	115	140	166	195	226	260
52			64	83	105	129	157	186	219	254	291
56			71	93	117	144	174	207	243	282	324
60			78	102	129	159	192	228	273	309	357
64					142	174	210	250	298	340	391
68					155	190	228	272	324	370	425
72								293	350	400	458
76								314	376	427	489
80								334	392	455	520

[a]Capacities allow one foot unused depth for settling in silos up to 30 ft high, and one additional foot for each 10 ft beyond 30 ft height.

Source: ASAE (1985)

Appendix B

Approximate Tons of Dry Matter in Next Four Feet of Silage in Top-Unloading Tower Silos During Unloading

This information is used in determining removal rates.

Depth of silage already unloaded (ft)	Silo diameter (ft)										
	10	12	14	16	18	20	22	24	26	28	30
0	1	2	2	3	4	5	6	7	8	9	10
4	1	2	3	4	5	6	7	8	10	11	13
8	2	2	3	4	5	7	8	10	11	13	15
12	2	3	4	5	6	8	9	11	13	15	17
16	2	3	4	5	7	9	10	12	14	16	18
20	2	3	5	6	7	10	12	14	16	18	22
24	3	4	5	7	9	11	13	15	18	21	23
28	3	4	5	7	9	11	14	16	19	22	26
32	3	5	6	8	10	12	14	17	20	23	27
36	3	5	6	8	10	12	15	18	21	23	27
40			7	8	10	13	16	19	22	27	30
44			7	9	11	13	17	20	23	27	31
48			7	9	12	13	17	20	24	27	31
52			7	9	12	14	17	21	24	27	33
56			7	10	12	15	18	21	25	28	33
60			7		13	15	18	21	25	31	34
64					13	16	18	21	26	30	34
68								21	26	30	33
72								21	26	27	31
76								21	26	28	31

Determining Removal Rate from Tower Silos

$$\text{Removal rate, inches/day} = \frac{(\text{Forage DM intake per cow, lb/day}) \times (\text{Number of cows})}{(\text{Tons DM in next 4 ft})} \times \frac{48}{2000}$$

Example: **100 Cows** each eat **15 lb** of haycrop silage DM per day and are fed from a 20 × 60 ft tower silo which was initially filled and has 20 ft of forage remaining.

The depth of silage already unloaded is 60 – 20 = 40 ft. From the above table, there are **13 tons** DM in the next 4 ft.

$$\text{Removal rate} = \frac{(15 \text{ lb/day}) \times (100 \text{ cows})}{(13 \text{ tons})} \times \frac{48}{2000} = 2.8 \text{ inches/day}$$

Approximate Dry Matter Capacities of Bunker Silos

Appendix C

Haycrop Silage

DM density is assumed to be 11.8 lb DM/ft^3 (Rotz, 1989).

$$\text{Capacity, tons DM} = \frac{(\text{Length, ft}) \times (\text{Width, ft}) \times (\text{Average height, ft}) \times 11.8}{2000}$$

Corn Silage

DM density is assumed to be 17.7 lb DM/ft^3 (Holter, 1983).

$$\text{Capacity, tons DM} = \frac{(\text{Length, ft}) \times (\text{Width, ft}) \times (\text{Average height, ft}) \times 17.7}{2000}$$

Determining Removal Rate from Bunker Silos, Haycrops

$$\text{Removal rate, inches/day} = \frac{(\text{Haycrop silage DM intake per cow, lb/day}) \times (\text{Number of cows})}{(\text{Silo width, ft}) \times (\text{Silage vertical depth, ft})}$$

Example: **50 cows** each eat **10 lb** of alfalfa silage DM per day and are fed from a **20 ft** wide, **12 ft** deep bunker silo.

$$\text{Removal rate} = \frac{(10 \text{ lb/day}) \times (50 \text{ cows})}{(20 \text{ ft}) \times (12 \text{ ft})} = 2.1 \text{ inches/day}$$

Determining Removal Rate from Bunker Silos, Corn Silage

$$\text{Removal rate, inches/day} = \frac{(\text{Corn silage DM intake per cow, lb/day}) \times (\text{Number of cows})}{(\text{Silo width, ft}) \times (\text{Silage vertical depth, ft}) \times 1.475}$$

Appendix D

Average Daily Pan Evaporation (mm) by Location and Month

	May	June	July	August	September	October
CALIFORNIA						
Alturas	5.0	5.8	7.0	6.7	4.7	2.9
Davis (non-irrigated)	7.6	9.0	9.8	8.6	7.0	4.6
Fresno	7.8	9.5	10.3	9.0	6.5	4.2
Oakland	4.7	5.4	5.4	5.0	4.5	3.3
Sacramento	6.9	8.9	9.4	8.4	6.4	4.2
San Diego	5.3	4.6	5.7	5.6	4.8	4.0
COLORADO						
Colorado Springs	6.6	7.8	7.9	7.2	5.6	4.3
Denver	6.2	7.5	8.2	7.6	5.5	4.0
Grand Junction	8.2	10.4	10.8	9.2	6.8	4.5
CONNECTICUT						
Bridgeport	4.0	4.6	4.8	4.5	3.6	2.9
Hartford	4.7	5.1	5.4	4.9	3.2	2.3
DELAWARE						
Wilmington	4.6	5.3	5.3	4.9	3.9	2.8
GEORGIA						
Atlanta	5.8	5.9	5.9	5.6	4.4	3.4
Augusta	5.2	5.5	5.4	5.3	4.2	3.5
Columbus	5.6	5.6	5.1	5.1	4.4	3.6
MAINE						
New Gloucester	5.1	4.2	5.1	4.7	3.3	NA
Portland	4.0	4.5	4.8	4.2	2.8	1.9
MARYLAND						
Beltsville	4.8	5.6	6.2	5.2	4.0	2.8
MASSACHUSETTS						
Rochester	3.8	4.5	4.8	4.0	2.8	1.8
Worcester	4.6	4.8	5.0	4.5	3.3	2.6
MICHIGAN						
Alpena	3.9	4.8	5.3	4.1	2.5	1.6
East Lansing	5.2	5.9	6.2	5.2	3.8	2.5
Grand Rapids	5.0	6.0	6.1	5.2	3.4	2.3

Average Daily Pan Evaporation (mm) by Location and Month

Appendix D

	May	June	July	August	September	October
MINNESOTA						
Duluth	4.3	4.7	5.5	4.4	2.6	2.0
Minneapolis	5.2	6.1	6.7	5.5	3.4	2.5
Waseca	5.4	7.1	7.2	5.7	4.3	NA
NEW HAMPSHIRE						
Concord	4.0	4.4	4.6	4.0	2.5	1.8
NEW YORK						
Aurora	4.5	5.4	5.9	4.9	3.4	2.4
Buffalo	4.3	5.5	5.9	4.8	3.4	2.3
Canton	4.9	6.1	5.9	4.7	3.1	2.2
Geneva	4.7	5.7	6.4	5.1	3.5	2.3
Ithaca	4.3	5.0	5.4	4.6	3.2	2.1
Mineola	5.3	6.1	6.8	5.7	4.5	3.2
PENNSYLVANIA						
Confluence	4.1	4.6	4.7	3.9	2.9	1.2
Harrisburg	5.2	5.9	6.4	5.4	3.7	2.6
Jamestown	3.9	4.7	4.0	2.7	2.0	NA
Pittsburgh	4.7	5.4	5.7	5.0	3.6	2.7
Scranton	4.6	5.2	5.3	4.6	3.1	2.2
VERMONT						
Burlington	3.8	4.7	5.0	4.3	2.6	1.8
WASHINGTON						
Olympia	3.3	3.9	4.9	4.1	2.6	1.2
Spokane	5.2	6.5	8.9	7.2	4.5	2.2
Yakima	5.5	6.5	8.1	6.6	4.4	2.4
WEST VIRGINIA						
Charleston	4.6	4.7	4.5	4.2	3.4	2.5
WISCONSIN						
Arlington	5.9	6.4	6.9	5.7	4.1	2.7
Green Bay	4.4	5.2	5.6	4.5	2.9	2.0
LaCrosse	5.2	5.9	6.1	5.2	3.2	2.7
Marshfield	5.5	5.5	5.9	5.2	3.7	2.7

Source: Farnsworth and Thompson (1982)

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