Engineering aspects of ensiling

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Abstract

Ensiling is a preservation method for moist forage crops, based on a lactic acid solid-state fermentation. Air is detrimental to silage because it enables the reactivation of detrimental aerobic microorganisms. The present review describes some of the major engineering and physical aspects of ensiling—silo types and the ensiling process—step by step. Issues considered include harvest and chopping, degree of consolidation, permeability to air ingress, sealing, additive application and unloading. Mathematical models that have been developed to simulate the ensiling process are mentioned. Experimentation methods are also described.

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1. Introduction

In modern dairy husbandry forage crops are harvested at a stage when yields and nutritional value are maximal; they are then preserved in order to ensure a continuous and consistent supply throughout the year. The major goal of preservation is to retain the highest possible proportion of the original nutritional value of the feed during storage. In the food industry many preservation methods are available: cooling and freezing, preservation by heat (blanching, pasteurizing, and commercial sterilization), drying, modified atmospheres, pickling and use of preservatives [1]. For economic and technical reasons, many of these methods are not applicable for forage crop preservation. Forage crops are preserved either by hay making (field drying) or by ensiling. Hay is preserved because its low water activity inhibits detrimental microbial activity. Hay making is restricted to crops that can dry quickly and uniformly, and to areas with little or no rainfall during harvest.

Ensiling is a preservation method for moist forage crops. It is based on solid-state lactic acid fermentation under anaerobic conditions whereby lactic acid bacteria (LAB) convert water-soluble sugars into organic acids, mainly to lactic acid. As a result the pH decreases, and the moist crop is preserved. Air is detrimental to silage because it enables plant respiration and the activity of aerobic spoilage microorganisms such as yeasts and moulds [2]. Therefore, many practices applied during ensiling, storage and feeding are intended to exclude air from the silage. Other practices that promote successful ensiling include the application of silage additives.

It is possible to ensile almost any plant material including plant by-products. The most important crops for ensiling worldwide are whole-crop corn, alfalfa and various grasses. Other crops include whole-crop wheat, sorghum and various legumes. Ensiling is a sophisticated and costly operation which is mainly used in developed countries. It is estimated that 200 million tonnes of dry matter (DM) are ensiled worldwide annually at a production cost between US$ 100 and 150 per tonne of DM. This cost comprises: land and cultivation (about 50%), harvesting and polyethylene (30%), silo (13%) and additives (9%) [3].

The ensiling process involves many steps that should be timed and controlled carefully in order to ensure successful ensiling with minimal losses. The present paper summarizes and reviews some of the major engineering and physical aspects of ensiling.

2. Brief description of the ensiling process

The ensiling operation consists the following steps: harvesting the crop at the optimal stage of maturity, wilting (if possible) to ensure adequate DM content depending on crop for a solid-state lactic acid fermentation, chopping, loading
into a silo, compacting and sealing to exclude air, storing and finally unloading for feeding to the animals. Additives can be applied during the chopping or loading steps.

The biochemical and microbiological events that occur during ensiling can be divided into four distinct stages:

1. **Aerobic processes** during filling and immediately after sealing while air is still present between the plant particles and the pH is 6.0–6.5. In this stage plant respiration continues as well as plant proteolysis and the activity of aerobic microorganisms such as enterobacteria, fungi and yeasts.

2. **Fermentation**, which is carried out by a dynamic succession of LAB which change according to the conditions prevailing in the silage, starting with *Enterococcus* and *Leuconostoc*, followed by *Lactobacillus* and *Pediococcus* species [4]. Lactic acid and organic acids accumulate, and the pH decreases to below 5.0, depending on plant composition and buffering capacity.

3. **Storage**, during which the silage is sealed, little air penetrates, and only few changes occur.

4. **Unloading** for feeding, during which the silage is reexposed to air, reactivating aerobic microorganisms, mainly yeasts and moulds, that may spoil the silage.

It is desirable to accelerate the fermentation step as much as possible in order to minimize the activity of detrimental microorganisms and to stabilize the silage. It is also important to minimize the exposure of the silage to air during storage and unloading. Many of the engineering aspects of ensiling are intended to help to achieve these goals and to obtain high-quality silage with minimal losses.

### 2.1. Silo types

Silos are the facilities in which the crops are fermented to silage and are stored until used for feeding. There are various types of silos, which are selected according to operator preference and feeding circumstances (Fig. 1). Silo capacity should be determined according to feeding needs (herd size and rations), and the dimensions should be calculated to remove an adequate depth of silage from the silo face daily to minimize silage exposure to air. The appropriate depth will be discussed later under the unloading section. The most abundant silo types include stack (clamp) without retaining walls, tower silo, bunker silo, horizontal plastic sleeve and big bale [5,6] (Fig. 1).

Stack silage consists a heap of chopped crop (typically 2–3 m high) which is compacted on bare ground or on concrete floor, with or without plastic sheeting at bottom, and sealed with plastic sheeting. It is used most often for relatively small quantities of silage in extensive farming, but maybe used on large intensive farms as well.

Tower silos are built of concrete or metal and maybe designed to be unloaded from the top or from the bottom. With this type of silo there is minimal exposure of the silage to air. The pressure exerted on the bottom of the walls by the weight of the herbage can cause serious problem of effluent flow and even damage the structure of the silo. Therefore, walls of concrete tower silos should be coated with a sealant, especially at the lower part of the silo where lateral and frictional forces exerted by the silage mass against the walls are highest. To avoid effluent, DM content of crops ensiled in tower silos should be higher than in bunker silos. The

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![Fig. 1. Silos for storing silage: (A) tower silos; (B) compaction silage in a bunker silo; (C) slilage bales; (D) silage in a plastic sleeve.](image-url)
minimal DM content to prevent effluent flow from tower silos depends on silo height and diameter. DM losses depend on silo wall permeability and on silage bulk density: the higher the density is, the lower the DM losses [7].

Horizontal bunker silos exist in various sizes and store large volumes of silage. They are made of concrete walls and floor. Their storage capacity depends on silo dimensions, DM content and forage type. Data on silo storage capacity have been compiled by Harrison and Fransen [8]. Bunker silos must be carefully managed in order to avoid exposure to air and consequent losses. Because of silage acids the iron reinforcement in the concrete is susceptible to rust and corrosion. Therefore, the walls should be treated periodically with tar and other coating materials such as epoxy. O’Donnell et al. [9] studied the characteristics of concrete that affect its corrosion by the acidic silage effluent. They exposed prisms of concrete prepared with various water:cement ratios to silage effluent for 28 days and measured the corrosion. A minimum cement content of 350 kg m\(^{-3}\) was needed to withstand corrosion. The seams between the concrete slabs should be tightly sealed in order to prevent air penetration. The top, shoulders and parts of the silage adjacent to the walls are most susceptible to air penetration and deterioration, and DM losses have been found to range between 3 and 10% in the center of the silage and 25–68% at the shoulders [10]. Deep silos have relatively less surface spoilage, and narrow silos have less face spoilage because a thicker layer is removed each day.

A comparison between the DM losses in bunker and tower silos is presented in Fig. 2 [11].

Plastics sleeves, called pressed bags in the US come in a variety of sizes, 1.8–3.6 m in diameter and length of 30, 60 and 90 m. They are filled by a portable bagging machine. They can also be partially filled, but should be tightly closed to prevent air pumping by billowing plastics.

Bales facilitate flexible use and can be brought individually to pasture sites according to need. Bales are made by wrapping individual units with four to eight layers of stretch polyethylene film, wrapped in a row with such film, or placed in a row inside a plastic sleeve like bagged silage. The bales vary in size but usually weigh 0.5–0.75 t (on wet basis). Baling of wilted crops is advantageous over direct cut crops: they result in better quality silages, their DM density is higher and therefore require less plastic and lower number of bales for a given mass of crop. There are two types of baling machines: fixed and variable filling chambers. In the former, the volume is constant so that the crop is subjected only to a rolling action and consequently, the core of the bale is less dense than the outer layers. In the variable chamber belt systems that cause the bale to rotate follow and compress the green mass as it enters, therefore, the bale density is more uniform. Square balers are also available. Bales are prepared from plants that were not subjected to chopping (usually grasses), and because of their high surface-to-volume ratio, bale silage is especially prone to aerobic deterioration. Bales should be handled with care in order to avoid tears in the wrapping.

Recently Ashbell et al. [12] showed that is possible to ensile forage in small plastic bags (10–20 kg) which can be used by small holder cattle owners in Africa. It was hypothesized that although such bags are not air-tight, the volatile fatty acids (e.g., acetic acid) that result from the fermentation accumulate in the bags and so inhibit aerobic deterioration.

Silage can be part of a feeding center that provides total mixed rations (TMR) and also stores concentrates and various feed supplements. Such a center is equipped with grinding mills, stationary mixers and conveyors. In Israel large regional feeding centers serve several thousand head of cattle on neighboring farms.
2.2. Effluent

If the DM content of the forage at ensiling is too low, effluent will result from the silage through which losses of nutritive matter occur. The volume of effluent maybe considerable depending on DM content, silo type, the degree of consolidation, the chopping length, bruising of the plants and the presence of acidic additives. Effluent is undesirable also because silo corrosion is enhanced; in addition, the very high BOD values of silage effluents (up to 50,000 mg O₂ l⁻¹ as compared with 500 of domestic sewage [7]) may cause environmental problems and pollution of water sources. Therefore, effluent should be drained into a manure pit or spread carefully in the fields. Effluent is produced if the DM content of the crop is below 30% in bunker and stack silos and at even higher DM contents in tower silos, because of the high pressure exerted by the weight of the silage. Effluent volumes from tower silos depend also on the height and diameter of the silo. The following examples demonstrate the effect of some parameters on effluent production: maize ensiled at 20% DM produced 53 and 271 of effluent per tonne, at chopping length of 6 and 32 mm, respectively [5]. Direct cut grass (15% DM) and grass wilted to 25% DM resulted in 200 and 21 effluent per tonne in bunker silo, with subsequent DM loss of 7.2 and 0.4%, respectively. At 30% DM no seepage was produced [7].

2.3. Harvesting

Different crops have differing harvesting practices. Wheat for example is harvested at the milk-dough maturation stage at 300 g kg⁻¹ DM and is subjected to a short wilting period before pick-up. This practice is intended to ensure the best nutritional quality and optimal ensiling properties. In addition, simultaneous harvesting and chopping would slow down the expensive harvesting process considerably, and would result in appreciable grain loss because of the aggressive rotating action of the discs. Small-grain cereals are susceptible to large grain losses because of their differing flow characteristics lead to separation of the grains from the vegetative parts at each handling step [13]. Legumes are wilted more intensively to make haylage in order to overcome problems associated with their high buffering capacity and subsequent effects promoting a butyric acid fermentation by clostridia if ensiled wet. It is not possible to wilt corn because of its thick stem; in arid areas its DM content is determined by the timing of the last irrigation, but in cold, moist areas it is determined by climate conditions when the crop is killed after the first frost. Combines for corn silage are equipped with a crushing device that damages the dry grains in order to increase their digestibility in the rumen.

In some cases (wet grasses and legumes primarily) it is recommended to wilt the crop in the field to obtain an adequate DM content (300-400 g kg⁻¹) necessary for the desired fermentation and in order to prevent effluent loss. Wilting depends mainly on solar radiation, and for rapid wilting it is recommended to spread the biomass in wide windrows in order to increase the surface area exposed to the sun and decrease the thickness of the crop. In rainy areas such as in northern Europe the wilting of moist grasses might be damaged by rain; if such moist grasses are not wilted, losses might occur through seepage production and undesirable clostridial secondary fermentation. Therefore, in such areas harvesting is planned for a sunny morning and pick-up of the wilted crop takes place in the afternoon. Sometimes plants are conditioned to enhance their loss of moisture; they are passed typically between intermeshing rubber or steel rolls of the mower-conditioner that bruise their waxy cuticle. Other machinery used in wilting include rakes, tedders and swath inverters. Losses during wilting arise from continuing plant respiration and the activity of aerobic microorganisms, and the extent of losses during this stage depends on the temperature during wilting and the initial DM content. Mechanical losses depend on the plant, the number of turning treatments and the DM content: the drier the crop the greater the losses. Legumes are of special concern because of their thin leaves, which dry out faster than the stems, become brittle and fall off during handling. This represents high nutritional losses. Respiration losses increase as the ambient temperature rises [14].

There is a wide variety of forage harvesters that include tractor-drawn, tractor mounted or self-propelled units. The usual power of modern harvesting combines is 200–225 kW and they consist of a basic modular unit to which can be added various units such as window pick-up for wilted crops, row crop mowers for direct chopping, choppers or sprayers to distribute additives [15]. The various chopper designs include sickle-bar and drum mowers; their capacity can be lesser or greater than 1 ha h⁻¹. Mowing is done with drum or flail mowers. With drum mowers, the forage is cut as it passes between a shear bar and knives mounted on a rotating cylinder head. The flail-type harvester consists of a series of cutting knives rotating at a high speed on a shaft. In the blower there is a second set of chopping knives. The harvester should be adjusted to the appropriate height in order to avoid mixing dirt and soil with the crop. Soil, rocks and debris can damage the knives. Soil also lowers the nutritional quality of the crop and increases its buffering capacity which interferes with the ensiling fermentation. In addition, the lower parts of the plants are usually inferior in quality, and therefore higher cuts are recommended. Harvesting should be timed to the optimal stage of maturity of the crop when yields, quality and ensiling characteristics are at their peak.

The recommended chopping length (1–2 cm) can be obtained by adjusting the number of knives on the chopping drum or by changing the speed gears of the feeding wheels. A short chopping length is useful for effective consolidation of the biomass, but some animal nutritionists feel that if the particles are too short, the silage loses its fibrous roughage properties that are necessary for good rumen function. Moreover, very short chopping may result in excessive effluent.
2.4. Transport

The chopped crop can be transported from the field to the silo by a variety of trucks and wagons of various sizes. The filling and unloading time depends on truck size, and the duration of the trip, i.e., on the distance from field to silo. Transportation capacity is affected by the number of vehicles used. Although transportation is a simple operation, it adds much to the cost of ensiling because of the high moisture content and the low density of the chopped crop.

2.5. Filling the silo

Filling should be as fast as possible in order to exclude air from the crop quickly and to minimize the losses that result from plant respiration and the activity of aerobic microorganisms. In bunker silos, the silo is generally filled in a series of wedges which are laid on top of one another so that the back of the silo reaches its capacity first. The silage is sloped in order to facilitate the drainage of rain and reduce the surface area exposed to air. Compaction in bunker and stack silos is accomplished by tractors which roll slowly back and forth continuously during filling. High specific pressure on thin forage layers is the most important factor which determines the degree of consolidation, and the specific pressure depends on the tractor characteristics (weight and whether it has single or dual wheels) and speed. The depth of the effect of rolling tractor is 20–40 cm from the surface [16,17], and it should be noted that the bunker should be at least twice as wide as the tractor to ensure that every strip along the silage can be compacted.

It is estimated that in a bunker silo the DM density of a well-compacted wheat silage at 350 g kg⁻¹ DM is 230 kg m⁻³ [15]. The DM density of barley and grass silages has been found to be 232 and 260 kg m⁻³, respectively [18]. DM densities of alfalfa and corn silages in a Wisconsin study varied between 106 and 434 kg m⁻³ [17], and the density was correlated with the thickness of crop layer being consolidated, tractor weight, packing time and DM content [17]. The higher the DM content and the longer the chopping length, the more difficult is the compaction because the crop is more resilient. Wheat at higher DM content is more difficult to compact because its hollow stem which is full of air. The lower the silage density in the silo is, the higher the DM losses [19]. Wall pressures in bunker silos are affected by wall slope, friction between silage and wall, the way in which the silage is piled above the top and the compaction method. Zhao and Jofriet [20,21] measured wall pressures during filling, compaction and after 3 months storage, and their results indicated that the wall loading exerted by the silage increases with depth from the surface at a rate of 5–7 kPa m⁻¹. The maximal wall pressure resulting from the weight of a 21t bulldozer was 10 kPa near the silage surface, i.e., 15% of the pressure under the bulldozer tracks. Wall pressures during compaction are a function of the tractor load and the distance of the vehicle from the wall. The effect of compaction becomes negligible at 2 m depth below silage surface.

In tower silos the consolidation is achieved by the weight of the forage itself. The density of the silage in a tower silo depends on the silage depth, DM content, crop characteristics and silo dimensions. Table 1 gives DM density as affected by silage depth [7].

The DM density of stack silage is similar to that of bunker silo and depends on crop DM content. At 25 and 35% DM content the DM density was 170 and 220 kg DM m⁻³, respectively [22].

The DM density in bale silage is strongly affected by the crop DM content. At 30 and 50% DM, the bale density is 100–150 and 150–200 kg DM m⁻³, respectively [23]. As mentioned before, DM density of bales made by fixed chamber balers is less uniform, and lower at the core of the bale.

2.6. Sealing

Sealing of bunker and stack silos is usually done with plastic sheeting, usually polyethylene of various thickness (0.1–0.2 mm). The plastic is anchored to the silage with used tyres, paper pulp or other materials that keep it from flapping. The plastic protects the surface of the silage against air penetration, and the thicker it is, the less oxygen permeable it is. The film should be UV resistant in order to withstand prolonged exposure to sunlight. Dickerson et al. [24] showed that in the top 250 mm, silage losses were 78 and 8% in uncovered and covered bunkers, respectively. Savoie [25] showed that the longer the storage period of the silage, the thicker the plastic needed to balance losses against the cost of the plastic. The thicker the plastic and the more densely placed the tyres, the fewer the physical tears caused by birds or rodents, and the smaller the resulting top losses [26].

Bale silage is wrapped with several layers of pre-stretched polyethylene film. For round bales, rotating table or rotating arm bale wrappers are available. When the number of layers of film increased from 2 to 6 silage quality improved significantly, with slower air penetration and much less mould development; film color (black, clear, green, light green and white) did not affect any of the ensiling parameters measured [27]. This is in contrast to the general belief that bales wrapped in black film might heat more than in white film due to light absorption/reflection properties.
2.7. Unloading

Losses during unloading depend on the duration of the exposure of the silage to air, the ambient temperature and the aerobic stability of the silage. Since air ingress into the silage from the unloading face depends on the silage density, the consolidation of the silage should be maintained during unloading, and the technology used for unloading affects this factor to a great extent: unloading with a front-mounted bucket tractor tends to produce a rough silage face which is more porous and offers a larger surface area and is therefore more susceptible to air penetration and increased DM loss than the smooth face left by a scraper type of unloader. Fig. 3 shows horizontal and vertical self-propelled silage scraper connected to a mixing wagon via a conveyer. Block cutters leave the unloaded silage compact; therefore, the blocks they cut can be stored for several days. Studies of gas composition within bunker silo indicate that air penetration into normally compacted silage is 1–2 m from the face [16,28]. In order to minimize the exposure of silage to air during feed-out it is recommended to renew the face often. The modeling work of Pitt and Muck [29] indicated that higher silage densities and faster removal rates for the exposed face predict substantially smaller aerobic losses.

2.8. Air penetration

Gas exchange in the silage depends on the flow caused by the pressure differences between the fermentation gas (usually CO₂) and air; this pressure difference is primarily caused by the difference in specific gravity between CO₂ and air. The flow intensity depends on the porosity of the silage (i.e., on the extent of compaction) and on leaks through the wall and sealing plastic. Reduction of the silage DM density by 20 kg m⁻³ might double the gas flow rate [16]. The permeability, porosity and density of the silage are interrelated properties, and are strongly affected by the moisture content [30]. A technique to measure the permeability of silage has been developed; it involves raising the pressure of an air reservoir, passing this air through the silage and measuring the exponential decay curve of the pressure [30]. The phenomena associated with gas flow and porosity of silage have been studied and modeled [19,31].

2.9. Silage additives

Silage additives can serve various purposes, and they are classified according to their function: fermentation stimulants, fermentation inhibitors, aerobic deterioration inhibitors, nutrients and absorbents [5]. There is a long list of available additives [32] which come in a variety of forms: liquid, powders or suspensions. Additives can be applied during the harvesting/chopping operation or during filling of the silo. For application of an additive suspension during chopping (bacterial inoculant for example), a special device should be mounted on the combine. It consists of a storage tank, a pump, tubing and a spray nozzle. The application rate is calculated according to the harvesting rate. Some powders or grainy materials are applied manually on top of every truck load and are mixed as soon as the tractor spreads the chopped forage into the silo.

3. Mathematical models of ensiling

Many mathematical models of the ensiling process have been developed. They take into account as many parameters as possible which might affect ensiling and express their
relative contribution to the changes which occur during ensiling in mathematical terms. These parameters include biochemical, microbiological and physical factors. Validation is an important step of the modeling process. Such models can be used to predict the ensiling process under various plant and ensiling conditions. Pitt et al. [33] designed such a model for mixtures of grasses, legumes and whole-plant corn. Parameters of the model were derived from published silage experiments and pure-culture bacterial studies. The model indicated the importance of initial LAB counts for the speed of the pH decline during ensiling. Another example is a model of silage consolidation and effluent flow [34], in which silage is modeled as a porous deformable medium containing a fluid. This model has been used to predict the importance of DM content and silo geometry in determining effluent production; it predicts that increasing the height/diameter ratio increases the time from initial drainage to the peak flow of effluent. Courtin and Spoelstra [35] presented a model that predicts the time-course of aerobic deterioration of grass and maize silage.

4. Silage research

Silage research addresses the various agronomical, biochemical, microbiological, nutritional and engineering aspects of the process. Much of silage research is performed to understand the complex processes that take place during ensiling in order to gain better control and higher quality of the preserved feed. Applied experiments for example may study the ensiling characteristics of newly introduced crops (e.g. Hedysarum coronarium, safflower) or of new cultivars of common crops or test the efficacy of various silage additives and new machinery. Ensiling experiments can be done under laboratory conditions in mini-silos in air-tight jars, or in on-farm conditions. Laboratory experiments enable the researcher to fill many jars and to sample successive jars for time-course studies of the fermentation process under various conditions. However, silages in mini-silos differ from commercial silages in their degree of consolidation and their gas exchange and heat transfer properties. In experiments under farm conditions, permeable nylon-mesh bags, containing control and treated forage and to which thermocouples and plastic tubing for gas sampling can be connected, can be buried in a farm-scale silo on the day of ensiling [28]. When the unloading front reaches the bags, they are analyzed in the laboratory. Experiments in which whole silos are treated require a similar control silo; such experiments are much more expensive but can be combined with animal feeding trials.

Silage quality is assessed according to sensory appraisal (appearance, smell, and texture), DM losses, pH, fermentation end products (lactic acid and volatile fatty acid profiles), protein breakdown and microbiological examination. Tests to assess the aerobic stability of silages include measurements of temperature increase during exposure to air or of CO2 production. A simple system constructed of recycled plastic soft drink bottles was developed by Ashbell et al. [36]: a silage sample weighing about 250 g is placed in the upper part of the system and a concentrated alkaline solution in the lower part. CO2 produced during aerobic exposure sinks and is measured along with pH, yeasts, moulds and visual appraisal (Fig. 4).

5. Future research needs

Ensiling is a preservation method for moist forage crops, whereby the crop is kept anaerobic and is fermented by LAB to attain a low pH (<5.0). Ensiling is a complex operation which requires careful management at all stages of silage making and use in order to obtain high-quality of preserved forage with minimal losses. The ensiling process involves many physical and engineering aspects. In the field of engineering in silage more research is needed: to improve the machinery used for harvesting, crushing and chopping, and to elucidate the flow properties of silage at different chopping lengths in the ration mixing wagon. The latter is especially important with inhomogeneous silage such as maize. Sealing technology and additive application also require improvement. Engineering aspects of forage hygiene especially in areas when manure is applied or where sewage irrigation is practiced, should be addressed.

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