**Intensive mechanical conditioning of forages: A review**

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Savoie, P. 2001. *Intensive mechanical conditioning of forages: A review*. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada 43:2.1-2.12. Intensive forage conditioning, also known as maceration, has been the object of research at several sites around the world over the last 20 years. Maceration has been shown to increase the field drying rate, to enhance the silage acidification rate, and to improve, in some instances, the dry matter intake or digestibility of forages fed to ruminants. In other instances, however, maceration has caused high losses and produced a low quality feed, especially under rainy or humid wilting conditions. The paper reviews various mechanisms proposed and several experiments carried out to evaluate field drying, power requirement, and feed value. Very intensive conditioning can be achieved by impact maceration followed by compression into a thin mat. Less intensive conditioning can be obtained with a small number of staggered rolls, without mat formation; such a treatment would be preferred in a more humid climate to minimize field loss. **Keywords**: forage, conditioning, maceration, drying, hay, silage.

**INTRODUCTION**

Forage losses tend to increase with prolonged field wilting (McGechan 1988). To reduce these losses, researchers have proposed various approaches to reduce the field wilting time. Thermal treatments such as heated rolls, heated air injection, or microwaves provide direct heat for water evaporation (Khalilian et al. 1992) and have been shown to improve the feed value by reducing proteolysis (Charmley and Veira 1990). Chemical treatments such as potassium carbonate solutions sprayed over the surface of the crop keep the stomata open for a prolonged period of time after mowing, thereby facilitating natural water evaporation (Rotz 1985). However, mechanical treatments such as roll conditioning (Rotz and Sprott 1984; Shinners et al. 1991; Borreani et al. 1999) are generally more practical and more economical than thermal or chemical treatments. Novel mechanical conditioning treatments can be more easily adopted when they are integrated in a machine already used on the farm, such as a mower, or become available in a form similar to other machines already used, such as tedders, windrow inverter, or rakes.

Very intensive mechanical conditioning, also known as maceration, has been the object of research at several sites around the world over the last two decades. Krutz et al. (1979) proposed an intensive forage conditioning concept that consisted of two corrugated steel rolls turning at high, but different speeds with a narrow clearance between the rolls. The peripheral speed difference caused a shearing effect on the crop, considerable cell rupture, a release of intracellular water and extremely rapid water evaporation. To minimize the loss of detached leaves and nutrient-rich juice, the macerated forage was compressed into a thin mat (about 5 to 10 mm thick) which was deposited delicately onto the stubble. Forage juice extracted during conditioning was channeled on top of the mat where soluble nutrients would dry and be retained. Related patents were obtained by Krutz (1979, 1981), Cicci (1982), and Holdren (1982). These patents covered the concept of intensive mechanical conditioning of forages but did not provide enough detail to develop effective mechanisms that could be applied in field working machines. Since then, several prototype macerators have been developed and evaluated under various conditions.

The objective of this paper is to review some of the engineering developments, to summarize the impact of maceration on the feed value of forages, and to discuss future perspectives for intensive mechanical conditioning of forages. The review emphasizes developments and potential applications under Canadian conditions.

**ENGINEERING DEVELOPMENTS**

**Macerator design**

Three types of macerator designs have received the most attention: the peripheral roll macerator, the staggered roll macerator, and the crushing-impact macerator (Fig. 1).

**Peripheral roll macerator** This design was developed by a research group in Wisconsin (Koegel et al. 1988). A field
Fig. 1. Three configurations for intensive forage conditioning: (a) peripheral roll macerator; (b) staggered roll macerator; (c) crushing-impact macerator.

Fig. 2. Experimental field prototype with cutterbar mower, eight staggered rolls, and a belt press (Savoie et al. 1993).

Fig. 3. Experimental field prototype with disc mower, staggered rolls, and slatted conveyor press (Savoie et al. 1997).

Working prototype consisted of a 1.2 m wide cutterbar, a 0.7 m wide maceration unit composed of seven small (0.1 m diameter) peripheral rolls turning around a larger (0.4 m diameter) central roll, and a belt-and-drum press to form the mat. Field evaluation showed that the wilting time to dry alfalfa to a moisture below 20% (i.e. a level considered safe for hay conservation) could be reduced to less than 6 h with the macerator (Shinners et al. 1987). This was a considerable improvement compared to the typical 3-d time period required in Wisconsin with conventional haymaking equipment. The peripheral roll macerator design was also evaluated by other researchers, notably in Germany (Schurig and Rödel 1989; Bischoff et al. 1989) and Turkey (Öztekin and Özkan 1997).

Several technical issues were raised as a result of the use of very intensive mechanical conditioning. The formation of a cohesive mat (see below) was required to minimize handling losses of the highly bruised material. Shinners et al. (1988a) compared various numbers of rolls and roll speed ratios to optimize the process in terms of maceration effectiveness and energy requirement. They suggested five planetary rolls and a speed ratio of 1.5:1. A commercial attempt was made to introduce the peripheral roll macerator in the early 1990's (Schmittbetz and Liebers 1991; Deutz-Fahr 1993) but was not conclusive.

Staggered roll macerator

This design was also developed in Wisconsin but first reported and evaluated in Québec as a result of collaborative work with the Wisconsin group (Savoie and Beauregard 1991a). A field mower-macerator prototype was built in 1991 and composed of a 2.1 m wide cutterbar, eight staggered rolls and a belt press (Savoie et al. 1993a; Fig. 2). The staggered roll design was simpler in terms of roll fabrication than the peripheral roll design because all rolls could be of the same diameter. The Prairie Agricultural Machinery Institute in Manitoba developed a simple two-roll staggered macerator adapted to a cutterbar mower (May 1994; PAMI 1994, 1996). It was very efficient in terms of reducing the wilting time for alfalfa under the relatively dry conditions of Manitoba.

Under more humid conditions in Québec, Savoie et al. (1997) developed a four-roll staggered macerator for a disk mower (Fig. 3). They obtained relatively high throughputs and
good drying rate increases in the field. Subsequently, the same research group developed a three-roll staggered macerator adapted to a 4.2 m wide cutterbar for a self-propelled mower-macerator (Savoie et al. 1999b; Fig. 4). These prototypes had throughputs of more than 50 t of fresh crop per hour. Because these conditioners had a less intensive maceration level compared to the peripheral roll macerator, they allowed forming windrows without the need to compress into a thin mat. A patent was obtained for a three-roll macerator (Savoie and Lajoie 2000) but this configuration has not yet been developed commercially.

Crushing-impact macerator This type of macerator was proposed as a simpler alternative to the peripheral roll macerator (Kraus et al. 1990, 1992; Koegel et al. 1992b). It consisted of two crushing rolls and an impact rotor (Fig. 1c). The forage was broken into ribbon-like fibre as it struck the rotor. The researchers observed that this design required considerably less energy than the peripheral roll macerator for a similar level of conditioning. Several patents have been obtained for crushing-impact maceration (Koegel et al. 1992a; Haldeman et al. 1999; Kraus et al. 2000a, 2000b).

Impact maceration, without crushing, was attempted commercially (Krone 1993) as a windrow handling treatment to be applied after mowing. Crushing maceration, without impact, was proposed by Nishizaki et al. (1997). Four pairs of crushing rollers exerted a high pressure on the fresh crop to break the stems longitudinally. However, none of these crushing or impact macerators has yet been developed commercially.

Mat forming system Because maceration destroys the physical integrity of the stems, frees up juice, and detaches leaves, various compression devices were developed to agglomerate the bruised mass into a cohesive mat. The objective of the mat forming system was to place the macerated forage on the stubble for rapid wilting and subsequent handling without excessive loss. Work carried out in the early 1980’s in Wisconsin used either a platen press or a roll press to study the wet strength and the drying rate of macerated forage mats (Risser et al. 1985; Shinners et al. 1985). A number of other press designs were developed subsequently with the objective of forming a cohesive mat continuously during mowing-maceration.

Belt press The basic idea of the belt press can be visualized in Fig. 2. The macerated forage is deposited onto a wide belt (typically 1.2 m or wider). A second belt of the same width moving in the same direction converges against the first belt to compress the forage mass into a thin layer (typically 5 to 10 mm thickness). The two belts are compressed by moving together between a series of compression rolls. Eventually the two belts separate and the compressed forage mat is released onto the stubble. Usually, an escape route is required for juice produced during compression. One approach is the use of a perforated belt and the deflection of juice back on top of the mat as it is deposited onto the stubble.

Wheel press A series of parallel wheels can be used to compress macerated forage. The forage moves on a conveyor and is compressed as it passes over a large roll of constant central axis. A series of parallel wheels is pushed down over the macerated forage and exerts a pressure to form a mat.

Slatted conveyor press A slatted conveyor press is made of two conveyor belts composed of rigid slats (Fig. 3). The lower and upper conveyors each move around rolls of constant central axes. The macerated forage is fed between the two conveyors while press plates, positioned within the upper conveyor, compress the forage. This system requires a low friction coefficient between the press plates and the moving slats, usually made of smooth plastic. Savoie et al. (1997) observed that such a press could be used to form a mat; it worked best with hydraulic power and an oil droplet spreading system to maintain excellent lubrication and minimize friction between the press plates and the slats.

No press The design of a high capacity press system is not a trivial matter. One problem is the relatively high power required. For example, Savoie et al. (1997) estimated a hydraulic power requirement of about 13.1 kW for compression when the dry matter (DM) flow rate was 6.7 t DM/h (i.e. a specific energy requirement of about 2 kW h/t DM). Another problem, especially with the belt-type press, is the requirement of a belt guidance device because of strong lateral forces that occur under non-uniform forage flow. To overcome these difficulties, May (1994) and Savoie et al. (1997) suggested a slight reduction of the maceration intensity to eliminate the need for a compression system. However, less intensive maceration was observed to have a smaller benefit on the field drying rate (see below).

Technical assessment of forage maceration

Field drying Table 1 reports 10 comparisons of the field drying coefficient for macerated forage versus a control. The drying rate is defined as the decline of moisture concentration per unit time. The drying coefficient, usually expressed as variable $k$, is a constant value during the wilting period and is defined as the natural logarithm of the moisture ratio (initial moisture concentration over final moisture concentration, on a dry basis) divided by the time interval (Rotz and Chen 1985). Values reported in Table 1 are relative increases of the drying coefficient following maceration, i.e. $(k_{macerated} - k_{control}) \times 100\% / k_{control}$.

In all 10 experiments, the drying coefficient was increased after maceration, by 26 to 160%. Increases tended to be higher.
The density should not be greater than 0.45 kg DM/m² for achieving very rapid drying. Savoie et al. (1992) suggested that compressed mats should have a maximum thickness of 6 mm to improve the drying coefficient. Periods in Manitoba with alfalfa exposed to a relatively dry environment (May 1994) showed a large drying coefficient increase (+125%) observed over a 50 h period. One exception was the persistently macerated swaths. Shinners et al. (1985) suggested that absorption area of solar radiation for both conventional and spreading forage as wide as possible in the field increases the drying coefficient increase across environments. Sundberg and Thyle (1994) reported that a higher number of maceration intervals attenuated the advantage of maceration. Dew or rain early stages of drying. Over a longer wilting time, the night-time conditions. The macerated windrows lost water rapidly in the early stages of drying. Over a longer wilting time, the night-time interval attenuated the advantage of maceration. Dew or rain absorption tended to be higher in the macerated crop and could decrease by as much as two thirds. Therefore, reducing the power requirement is a constraint. The macerator when available power is a constraint.

The crop density in the swath affects the drying rate. Spreading forage as wide as possible in the field increases the absorption area of solar radiation for both conventional and macerated swaths. Shinners et al. (1985) suggested that compressed mats should have a maximum thickness of 6 mm to achieve very rapid drying. Savoie et al. (1992) suggested that the density should not be greater than 0.45 kg DM/m² for macerated alfalfa to dry to less than 20% moisture in a day of sunshine. If the yield is greater than 4.5 t DM/ha, then it is impossible to spread the material sufficiently to reach that goal. With ryegrass, Savoie et al. (1994) also observed a rapid drying rate when the swath density was relatively low at 0.4 kg DM/m²; dry hay could be obtained after energy absorption equivalent to a pan evaporation of 5 mm. Maceration is more effective in a low yielding crop that is well spread out in the field, as suggested by McGechan et al. (1991).

Table 1. Effect of maceration on forage drying rate.

<table>
<thead>
<tr>
<th>Type of macerator</th>
<th>Crop</th>
<th>Drying time (h)</th>
<th>Drying coefficient increase (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-roll peripheral + press</td>
<td>alfalfa</td>
<td>6</td>
<td>160</td>
<td>Shinners et al. (1987)</td>
</tr>
<tr>
<td>5-roll peripheral + press</td>
<td>ryegrass</td>
<td>7</td>
<td>126</td>
<td>Schurig and Rödel (1989)</td>
</tr>
<tr>
<td>8-roll staggered + press</td>
<td>alfalfa</td>
<td>9</td>
<td>137</td>
<td>Savoie et al. (1993a)</td>
</tr>
<tr>
<td>2-roll staggered + press</td>
<td>timothy</td>
<td>9</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>6-roll peripheral (no press)</td>
<td>alfalfa</td>
<td>50</td>
<td>125</td>
<td>May (1994)</td>
</tr>
<tr>
<td>3-roll staggered + press</td>
<td>alfalfa + timothy</td>
<td>30</td>
<td>30</td>
<td>Öztekin and Ozkan (1997)</td>
</tr>
<tr>
<td>3-roll staggered (no press)</td>
<td>alfalfa + timothy</td>
<td>33</td>
<td>30</td>
<td>Savoie et al. (1997)</td>
</tr>
<tr>
<td>3-roll staggered (no press)</td>
<td>clover, early</td>
<td>34</td>
<td>26</td>
<td>Savoie et al. (1999b)</td>
</tr>
<tr>
<td></td>
<td>clover, late</td>
<td>34</td>
<td>65</td>
<td>Descôteaux and Savoie (1999)</td>
</tr>
</tbody>
</table>

Table 2. Specific energy required to operate the macerator.

<table>
<thead>
<tr>
<th>Type of macerator</th>
<th>Specific energy (kW h/t DM)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-roll peripheral</td>
<td>9.2</td>
<td>Rotz et al. (1990)</td>
</tr>
<tr>
<td>3-roll crushing impact</td>
<td>2 - 4</td>
<td>Kraus et al. (1992)</td>
</tr>
<tr>
<td>8-roll staggered</td>
<td>3.8</td>
<td>Tremblay et al. (1994)</td>
</tr>
<tr>
<td>3-roll staggered, on disk mower</td>
<td>4</td>
<td>Savoie et al. (1997)</td>
</tr>
<tr>
<td>3-roll staggered, laboratory</td>
<td>3 - 4</td>
<td>Savoie and Tremblay (1997)</td>
</tr>
<tr>
<td>3-roll staggered, on self-propelled mower</td>
<td>2 - 2.6</td>
<td>Savoie et al. (1999b)</td>
</tr>
</tbody>
</table>

The power requirement of conventional mower-conditioners is sometimes expressed per unit mower width, independent of forward speed or mass flow. For example, ASAE (1999; Engineering Data D497.4) suggests a power requirement of 4.5 kW/m for a cutterbar mower-conditioner and 8.0 kW/m for a disk mower-conditioner. However, when mass flow is considered as an important variable, power required for mowing-conditioning should be based on energy per unit processed mass as was reported by Rotz and Sprott (1984) who estimated fuel consumption between 0.24 and 0.84 L/t DM. These values correspond approximately to a range of 0.75 to 2.5 kW h/t DM, assuming an energy conversion of 3 kW h at the power takeoff shaft per litre of fuel which takes into account engine efficiency. The cutterbar-roll conditioner had the lowest energy requirement (0.75 kW h/t DM) and a disk-flail conditioner had the highest (2.5 kW h/t DM). A typical 60 kW tractor with 40 kW available to the PTO can therefore mow and condition over 15 t DM/h (i.e. 3 ha/h or 75 t fresh crop yielding 5 t DM/ha at 80% moisture). If maceration and mat forming require an additional 4 kW h/t DM, an extra 60 kW at the PTO would be needed to maintain the same mass-flow-rate. If extra power is not available, the mass-flow-rate will have to be decreased by as much as two thirds. Therefore, reducing the number of macerating rolls and reconsidering the need to form mats are important issues in designing a practical mower-macerator when available power is a constraint.

Straits et al. (1989) observed that the power to harvest and chop forage was lower with macerated windrows than...
conventional windrows. Tremblay et al. (1994) reported data showing about 25% less power required (20 kW vs 26 kW at the PTO) when harvesting macerated windrows at a moderate mass-flow-rate (6 t DM/h). The lower power requirement to chop and blow macerated windrows was due mainly to a lower moisture content and a more mixed, obliquely oriented crop which resulted in a greater mean particle length compared to a conventional windrow chopped at the same theoretical length-of-cut setting.

Other technical issues Research related to roll surface has received little attention. The typical surface of peripheral or staggered rolls is formed of a series of longitudinal grooves with pointy or slightly flattened apexes (Fig. 5). Savoie and Tremblay (1997) reported an experiment using one helically grooved roll and two longitudinally grooved rolls. This configuration produced a drying rate similar to the one obtained with a macerator composed of three longitudinally grooved rolls. Both configurations increased the drying coefficient of alfalfa by 85% compared to a non-conditioned control. The helically grooved roll is interesting because of its lower fabrication cost compared to a longitudinally grooved roll. However, further evaluation would be required to optimize the roll surface versus the cost of fabrication of the rolls.

Another technical issue is the hardness and durability of the roll surface. Since most field prototypes have been used only for a limited time, there is not enough data at this stage to compare various roll surfaces and their durability. There is empirical evidence with soft iron rolls that the apexes become dull and rounded within 100 to 200 hours of use. Therefore, a process of steel hardening should be applied to macerating rolls to prolong their useful life to that of typical mower-conditioners (i.e. 1000 to 2000 h).

The development of various maceration prototypes in different countries has made it difficult to compare results because of differences in the level of mechanical conditioning. A number of methods have been proposed to quantify mechanical conditioning: diffusion of K$^+$ ions in a water solution (Locus et al. 1994), compressibility of forage under a fixed pressure (Savoie et al. 1996a), and the electrical conductivity of leachate obtained from the conditioned forage (Kraus et al. 1999). As the forage is increasingly macerated, ions and soluble constituents are more easily released. Similarly, the forage is more easily compressed. There is not a single, standard method currently used to assess the level of mechanical conditioning. However, such a standard would facilitate comparison of intensive forage conditioning treatments at various sites.

The pick-up of macerated windrows has been a concern because of potentially large losses. The broken nature of the particles and the fragility of mats require a delicate pick-up system. Straub et al. (1989) suggested a belt pick-up unit instead of the traditional tine pick-up unit. Savoie et al. (1993a) did not find significant differences in pick-up losses between the two systems. A reduction of the intensity of maceration has also been found to alleviate the fragility of the macerated windrow and the concern with pick-up losses.

Maceration was initially developed as an integral part of the mower to combine mowing and intensive conditioning in a single operation. While maceration may be highly beneficial under good drying conditions, it is deleterious under rainy conditions. Therefore, it cannot be applied systematically, especially in areas with a variable climate. For this reason, Descôteaux and Savoie (1999) developed a pull-type macerator that could be applied after mowing as an independent operation (Fig. 6). Such a macerator presents a dual advantage: reduced cost to adopt maceration (less costly than a mower-macerator) and the possibility of applying maceration as an optional

![Fig. 5. Side view of a typical macerator roll (Savoie et al. 1999b).](image_url)

![Fig. 6. Three-roll staggered macerator operated with a windrow pickup (Descôteaux and Savoie 1999).](image_url)
treatment, only if weather forecasts are favourable. In the long run, however, it seems more efficient to integrate maceration with the mower and to develop controls that would modify the level of maceration according to the crop processed and the weather forecasts.

Another technical issue is the collection of forage juice during the mowing-maceration process. Forage juice can be processed into various components that may be sold on high value markets such as soluble protein, xanthophyll, and beta-carotene (McGuckin et al. 1982). Maceration and compression into a mat have been shown to extract up to 15% of the fresh mass (Savoie and Beauregard 1991b). If there is a market for forage juice and extracted products, maceration-compression can be used as a first step for collecting the juice in the field. However, if there is no market for such extracts or if the economics are not favourable, then the forage juice is best valued by simply returning it onto the forage. One design, that includes a perforated belt (Fig. 2), redirects the juice on the top surface for retention of soluble nutrients in the windrow (Savoie et al. 1993a).

**FEED VALUE OF MACERATED FORAGES**

**Forage quality**

Maceration can affect forage quality in several ways: increased mechanical loss by shattering, reduced respiration loss as a result of rapid drying and lower moisture content, increased leaching loss from the bruised surface if it is exposed to rain, and improved lactic fermentation of silage. This section focuses on forage quality; the following section considers animal performance.

**Effect of maceration on mechanical loss**

Maceration can break leaves and stems into small particles which become more susceptible to loss. When the macerated windrow is subsequently turned, raked or picked up by a baler or a forage harvester, each manipulation can cause further mechanical loss. For this reason, windrow handling should be reduced to a minimum of delicate operations.

Savoie et al. (1993a) observed 3.5% DM loss from forage treated with a conventional mower-conditioner and 7.8% for forage treated with an 8-roll staggered macerator. Savoie et al. (1997) observed 6.6% DM loss for conventional mowing-conditioning and 7.2% DM loss for macerated forage with a 3-roll staggered macerator. These authors did not distinguish the proportion of leaves versus the proportion of stems that were lost, but hypothesized that a greater proportion of leaves was lost. This hypothesis is supported by the fact that the nutritional quality almost always decreases after maceration (see below, chemical composition). The feed value of leaves is considerably greater than that of stems. For example, alfalfa leaves contain about 35% crude protein (CP) and 20% acid detergent fibre (ADF) while stems contain 14% CP and 50% ADF (Savoie 1988). A greater loss of leaves will decrease the protein content and increase the fibre content of the harvested forage.

**Effect of maceration on respiration and leaching loss**

Maceration creates a large exposed area on which microorganisms may grow and rapidly releases some of the intracellular soluble sugars. Therefore, microorganism growth and respiration rate can be increased at the beginning of wilting because of maceration. However, when macerated forage dries very quickly, the amount of water needed for microorganism growth becomes limiting more rapidly than in a conventionally conditioned crop. Maceration followed by rapid drying will actually reduce total crop respiration in the field.

If maceration is followed by slow drying due to rain or humid conditions, respiration will actually increase. This increased respiration is partly a result of the large, broken area on which microorganisms will grow. Respiration is also facilitated by the high moisture conditions which prevail under slow drying. Maceration also causes a rapid release of soluble sugars which represent an excellent substrate for microorganism growth.

A small number of experimental studies have confirmed this ambivalent effect of maceration on respiration and leaching losses. Rotz et al. (1991) observed that 18 mm of rain caused 15% DM loss in macerated alfalfa and only 4% DM loss in rubber-roll conditioned alfalfa. After 62 mm rainfall, DM losses were 27 and 7%, respectively. Savoie et al. (1993b) also noted more losses in macerated alfalfa (20%) than in unmacerated alfalfa (13%) after 6 mm of rain. Timothy grass was less affected by loss after rain (8% if macerated, 7% if unmacerated). When no rain occurred and drying conditions were excellent, respiration loss of alfalfa windrows was actually lower: 5% for macerated alfalfa and 12% for unmacerated alfalfa (Savoie et al. 1993b). The same study reported 0% loss for macerated timothy and 2% for unmacerated timothy under excellent drying conditions. Sundberg and Thylén (1994) observed that rain caused 1 to 2% loss of DM in conventionally conditioned forage. After maceration, they observed about 10% DM loss for grasses and 20% DM loss for legumes subjected to 18 or 25 mm of rain.

Kraus et al. (1998) measured the production of carbon dioxide to estimate DM loss. Alfalfa was incubated over a 48 h period at two temperatures (11 and 31°C) and two moisture contents (MC of 79 and 55%). At low temperature and high moisture, the DM loss was 1% for macerated forage and 2% for unmacerated forage. At high temperature and high moisture, the DM loss was 14% for macerated alfalfa and 6% for unmacerated alfalfa. When alfalfa was drier (55% MC), losses were considerably lower with less difference between macerated and unmacerated crops. These data confirm that maceration will cause greater respiration when the crop is wet and exposed at a high ambient temperature, while at a low temperature and low moisture content, respiration will almost cease.

**Effect of maceration on silage fermentation**

Studies by Muck et al. (1989) and Bischoff et al. (1989) indicated that maceration accelerated pH decline in chopped alfalfa and grass silages as a result of greater growth rate of microorganisms, faster availability of soluble sugars, and more rapid production of organic acids during the early stages of fermentation. Since maceration destroys the plant structure, natural compaction of chopped forage is easier and a large proportion of oxygen originally present is naturally evacuated, especially in tower silos (Shinners et al. 1988b). Savoie et al. (1996b) also observed a faster decline of pH in the early hours after wrapping macerated forage in large round bales conserved as silage.

Charmley et al. (1997) found a very high count of colony-forming units (cfu) for wilted and macerated alfalfa at the time of ensiling. They observed 10⁶ cfu/g of silage after maceration.
Maceration has been reported to reduce proteolysis, i.e. enzyme activity that degrades protein into amino acids. This relatively low fibre content minimized the loss of soluble sugars, and maintained a moisture content in the crop, reduced respiration activity, and wilting (35% DM), compared to 10^7 cfu/g of silage for unmacerated, wilted forage (26% DM). The pH decline was faster and the proportion of lactic acid over total organic acids was higher (56% vs. 50%), indicating a higher degree of homolactic fermentation after maceration. However, when forage was not wilted but stored very wet (15% DM), maceration also increased microorganism activity but this included heterolactic fermentation and a lower proportion of lactic acid (47%) after maceration than without maceration (52% lactic acid/total acids). Very wet silages are known to further inhibit protease activity in the silo due to the higher likelihood of a lower moisture content at ensiling.

Under ideal wilting conditions, maceration is expected to result in very rapid drying and lower respiration and protease activity. However, under humid or rainy conditions, maceration will increase the field respiration and protease activity, thereby increasing the loss of soluble sugars and the degradability of true protein. Therefore, maceration can be observed to either improve or reduce the feed quality of forage, depending on the environment.

**Effect of maceration on overall chemical composition**

Table 3 presents the forage fibre content of macerated and unmacerated (control) forages in seven different experiments. In general, fibre concentration increased after maceration, especially when rain occurred during wilting. When drying conditions were ideal, e.g. under full sunshine or in the laboratory without rain (Savoie et al. 1993b; Agbossamey et al. 1998), maceration accelerated drying, reduced more rapidly the moisture content in the crop, reduced respiration activity, minimized the loss of soluble sugars, and maintained a relatively low fibre content.

Maceration has been reported to reduce proteolysis, i.e. enzyme activity that degrades protein into amino acids. This inhibition of proteolysis is explained by the more rapid reduction of moisture content which reduces protease activity. Agbossamey et al. (1998) observed that alfalfa and timothy, dried in the laboratory under ideal conditions, had less soluble N (mainly amino acids) and more slowly degradable N (true protein) after maceration compared to a control. They observed similar results with alfalfa conserved as silage. Maceration can further inhibit protease activity in the silo due to the higher likelihood of a lower moisture content at ensiling.

**Table 3. Forage fibre content after maceration and rain.**

<table>
<thead>
<tr>
<th>Crop species</th>
<th>Wilting environment</th>
<th>Measured variable</th>
<th>Control*</th>
<th>Macerated</th>
<th>Statistical significance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>Lab, 0 rain</td>
<td>NDF (%)</td>
<td>43.3</td>
<td>46.7</td>
<td>NR</td>
<td>Hong et al. (1988a)</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>(on plastic)</td>
<td>ADF (%)</td>
<td>35.4</td>
<td>37.3</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Lab, 0 rain</td>
<td>NDF (%)</td>
<td>43.1</td>
<td>46.2</td>
<td>P &lt; 0.01</td>
<td>Rotz et al. (1991)</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Lab, 18 mm rain</td>
<td>NDF (%)</td>
<td>44.6</td>
<td>54.2</td>
<td>P &lt; 0.01</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Lab, 62 mm rain</td>
<td>NDF (%)</td>
<td>45.6</td>
<td>60.2</td>
<td>P &lt; 0.01</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Lab, 0 rain</td>
<td>ADF (%)</td>
<td>29.6</td>
<td>27.6</td>
<td>NR</td>
<td>Savoie et al. (1993b)</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Lab, 6 mm rain</td>
<td>ADF (%)</td>
<td>30.0</td>
<td>32.5</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>Timothy</td>
<td>Lab, 0 rain</td>
<td>ADF (%)</td>
<td>32.9</td>
<td>32.3</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>Timothy</td>
<td>Fab, 6 mm rain</td>
<td>ADF (%)</td>
<td>34.9</td>
<td>35.3</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>Timothy</td>
<td>Field, 0 rain</td>
<td>ADF (%)</td>
<td>39.2</td>
<td>45.5</td>
<td>P &lt; 0.05</td>
<td>Petit et al. (1994)</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Field, 0 rain</td>
<td>ADF (%)</td>
<td>43.3</td>
<td>52.6</td>
<td>P &lt; 0.05</td>
<td></td>
</tr>
<tr>
<td>Timothy</td>
<td>Lab, 0 rain</td>
<td>ADF (%)</td>
<td>34.3</td>
<td>33.9</td>
<td>NS</td>
<td>Agbossamey et al. (1998)</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Lab, 0 rain</td>
<td>ADF (%)</td>
<td>38.5</td>
<td>38.3</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Field, 3.2 mm rain</td>
<td>ADF (%)</td>
<td>41.4</td>
<td>44.1</td>
<td>P &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Field, 0 rain</td>
<td>NDF (%)</td>
<td>34.7</td>
<td>37.4</td>
<td>P &lt; 0.05</td>
<td>Suwarno et al. (1999)</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>Field, 20 mm rain</td>
<td>NDF (%)</td>
<td>33.0</td>
<td>40.9</td>
<td>P &lt; 0.05</td>
<td></td>
</tr>
<tr>
<td>OG + WC</td>
<td>Field, 1 mm rain</td>
<td>NDF (%)</td>
<td>49.2</td>
<td>51.0</td>
<td>NR</td>
<td>Charmley et al. (1999)</td>
</tr>
<tr>
<td>OG + WC</td>
<td>Field, 1 mm rain</td>
<td>NDF (%)</td>
<td>32.4</td>
<td>36.0</td>
<td>NR</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: NDF = neutral detergent fibre; ADF = acid detergent fibre; OG = orchardgrass; WC = white clover
Lab = laboratory environment; NR = not reported; NS = not significant
*Control treatments were either untreated (not conditioned for Hong et al. 1998 and Agbossamey et al. 1998) or conditioned with intermeshing rubber rolls for the five other experiments.

**Animal performance**

Table 4 presents a summary of eleven animal experiments where four types of ruminants (dairy goats, dairy cows, sheep, or steers) were fed various forages (alfalfa, timothy, ryegrass, or orchardgrass) that were either macerated or not. In five experiments, macerated forage resulted in better animal performance (more milk production, greater dry matter intake (DMI) or improved gain to feed ratio). In the six other
Table 4. Effect of forage maceration on animal performance.

<table>
<thead>
<tr>
<th>Crop species</th>
<th>Feed species</th>
<th>Animal species</th>
<th>Measured variable</th>
<th>Control</th>
<th>Macerated</th>
<th>Statistical significance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>60% hay + 40% grain</td>
<td>dairy goats</td>
<td>DMI (kg/d)</td>
<td>2.44</td>
<td>2.58</td>
<td>P &lt; 0.01</td>
<td>Hong et al. (1988a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4% FCM</td>
<td>3.3</td>
<td>3.7</td>
<td>P &lt; 0.01</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>65% chopped silage, 35% grain</td>
<td>dairy cows</td>
<td>milk (kg/d)</td>
<td>24.5</td>
<td>24.2</td>
<td>NS</td>
<td>Koegel et al. (1992b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ADG (kg/d)</td>
<td>0.08</td>
<td>0.44</td>
<td>P &lt; 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MEF (MJ/kg)</td>
<td>4.61</td>
<td>5.11</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>hay + 10 kg/d grain</td>
<td>dairy cows</td>
<td>milk (kg/d)</td>
<td>29.9</td>
<td>34.3</td>
<td>P &lt; 0.05</td>
<td>Savoie and Block (1994)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>hay DMI (kg/d)</td>
<td>14.0</td>
<td>16.1</td>
<td>P &lt; 0.05</td>
<td></td>
</tr>
<tr>
<td>Timothy</td>
<td>100% mature hay</td>
<td>steers</td>
<td>DMI (kg/d)</td>
<td>10.5</td>
<td>10.3</td>
<td>NS</td>
<td>Chiquette et al. (1994)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DMD (%)</td>
<td>66.5</td>
<td>65.7</td>
<td>P &lt; 0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>EDDM (%)</td>
<td>36.0</td>
<td>39.9</td>
<td>P &lt; 0.05</td>
<td></td>
</tr>
<tr>
<td>Alfalfa + Timothy</td>
<td>100% hay</td>
<td>sheep</td>
<td>DMI (g/d)</td>
<td>899</td>
<td>971</td>
<td>P = 0.09</td>
<td>Petit et al. (1994)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DMD (%)</td>
<td>53.0</td>
<td>57.9</td>
<td>P = 0.006</td>
<td></td>
</tr>
<tr>
<td>Ryegrass</td>
<td>100% chopped silage</td>
<td>sheep</td>
<td>DMI (g/d)</td>
<td>830</td>
<td>780</td>
<td>NS</td>
<td>Frost et al. (1995)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DMD (%)</td>
<td>68.7</td>
<td>69.0</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>100% round bale silage</td>
<td>beef cattle</td>
<td>DMI (%BW)</td>
<td>2.77</td>
<td>2.91</td>
<td>P = 0.04</td>
<td>Suwarno et al. (1997)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ADG (kg/d)</td>
<td>0.9</td>
<td>1.0</td>
<td>P = 0.04</td>
<td></td>
</tr>
<tr>
<td>Timothy</td>
<td>72% hay + 28% grain</td>
<td>sheep</td>
<td>DMI (%BW)</td>
<td>3.98</td>
<td>3.80</td>
<td>P = 0.04</td>
<td>Petit et al. (1997)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ADG (g/d)</td>
<td>279</td>
<td>285</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GFR</td>
<td>0.217</td>
<td>0.235</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>OG + WC</td>
<td>100% round bale silage</td>
<td>beef cattle</td>
<td>DMI (%BW)</td>
<td>2.73</td>
<td>2.71</td>
<td>NS</td>
<td>Charmley et al. (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ADG (kg/d)</td>
<td>0.87</td>
<td>1.09</td>
<td>P &lt; 0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GFR</td>
<td>0.103</td>
<td>0.130</td>
<td>P &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>OG + WC</td>
<td>100% chopped silage</td>
<td>beef cattle</td>
<td>DMI (%BW)</td>
<td>2.15</td>
<td>1.76</td>
<td>P &lt; 0.05</td>
<td>Charmley et al. (1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ADG (kg/d)</td>
<td>1.00</td>
<td>1.03</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>GFR</td>
<td>0.148</td>
<td>0.184</td>
<td>P &lt; 0.001</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>100% chopped silage</td>
<td>sheep</td>
<td>DMI (%BW)</td>
<td>2.31</td>
<td>2.88</td>
<td>Q</td>
<td>Agbossamey et al. (2000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DMD (%)</td>
<td>60.8</td>
<td>60.1</td>
<td>L, Q</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: OG = orchardgrass; WC = white clover; DMI = dry matter intake; FCM = fat corrected milk; ADG = average daily gain; MEF = metabolizable energy of forage; DMD = dry matter digestibility; EDDM = effective degradability of dry matter; GFR = gain:feed ratio; P = probability level; NS = not significant; L and Q = linear and quadratic effects of maceration.

Experiments, macerated forage did not show any significant improvement. In two cases (Petit et al. 1997; Charmley et al. 1999 - chopped silage), maceration caused a significant decline of DMI but resulted in an improved gain to feed ratio. The animals ate less but used the macerated forage more efficiently for growth.

The improved nutrient utilization after maceration can be explained partly by the increased broken crop area which facilitates microbial colonization in the rumen. Hong et al. (1988b) used electron scanning microscopy to show that maceration actually separated lignified and unlignified cells, and damaged the external cuticular waxy layer. This can also explain why, in some instances, an apparently lower feed quality based on chemical composition might still result in equal or better animal performance compared to control forage. One example of such an apparent contradiction is the study by Hong et al. (1988a) who reported a lower CP and a higher NDF in macerated forage compared to the control. Sheep fed the macerated forage had nonetheless 5% higher DMI and 25% higher average daily gain (ADG) than the conventional hay. Similarly, Suwarno et al. (1997) reported that beef cattle fed macerated round bale alfalfa silage (16.8% CP; 49.8% NDF) had 6% higher DMI and 11% higher ADG compared to beef cattle fed non-macerated round bale silage with a nominally better chemical composition (18.1% CP; 48.2% NDF).

Maceration is also thought to increase the retention time of forage in the rumen because it is more compressible (Savoie et al. 1999a). The greater retention time should increase the overall digestion. Kraus et al. (1997) showed that ruminal digestion was faster during the first 24 h for macerated forage versus...
unmacerated forage, but the difference became smaller over a 48 h period. Hintz et al. (1999) suggested that high performance animals with rapid feed turnover rates would be expected to benefit most from maceration while animals at maintenance level will experience few if any nutritional benefit from maceration. With high yielding cows (38 to 47 kg milk/d), Broderick et al. (1999) observed that macerated alfalfa silage increased milk production in two trials out of four, and provided on average 4% more effective metabolizable energy (5.94 vs 5.69 MJ/kg) than control alfalfa silage. With lower yielding cows (24 kg/d), Koegel et al. (1992b) observed no milk production increase, but macerated alfalfa silage still provided 11% more metabolizable energy as a result of a greater mass gain. With mature, slow growing steers (average mass 711 kg), Chiquette et al. (1994) observed practically no animal performance gain: intake was similar, DM digestibility was lower, and rumen degradability was higher with macerated hay compared to control hay.

**FUTURE PERSPECTIVES**

**Livestock producers**

Maceration has two major advantages for livestock producers: reduction of the field wilting time and improvement of the forage feed value. However, maceration may result in a lower quality feed if the forage is exposed to rainfall or conserved as very wet silage. Another disadvantage is the higher cost of a mower-macerator compared to a conventional mower-conditioner, because of the more complex mechanisms.

Rotz et al. (1990) carried out an economic analysis of maceration on dairy farms under the climatic conditions of Michigan. They hypothesized that a pull-type mower-macerator would cost US$82,000 while a conventional mower-conditioner would cost US$9500. Considering the potential increase in feed value as a result of reduced field respiration and increased dry matter intake, they estimated that a dairy producer with 100 cows each averaging 8000 kg of milk per year could have a net income increase between US$10,000 and US$15,000 because of substantially lower purchased feeds.

Another economic study carried out in the United Kingdom (McGechan et al. 1993) estimated an increase in net farm income for dairy producers converting to maceration technology. The gain was greater for farmers with a hay conservation system than for farmers with a silage conservation system. In Sweden, Thylen and Sundberg (1995) did a simulation study considering multiple year climatic conditions. They concluded that maceration would considerably reduce the risk of weathering and generally improve the quality of conserved forages.

**Alfalfa processors**

The production of alfalfa cubes and pellets requires artificial drying which has been estimated to cost between US$5 and $30 per ton depending on the price of natural gas and the moisture content of alfalfa delivered at the processing plant (Berney 1987). Maceration can reduce the cost of artificial drying by reducing the moisture content of the harvested forage. Savoie et al. (1995) carried out a simulation study where they compared a self-propelled (SP) mower-macerator (CDN$90,000) versus a conventional SP mower-conditioner (CDN$60,000). Under a dry climate (20 to 30% daily rainfall probability), maceration was not beneficial. Under a wetter climate (40 to 50% probability of daily rainfall), maceration could increase the net income of the plant by CDN$14,000 to CDN$20,000 per mower typically used to harvest 5000 t of crop per year (a net gain of CDN$3 to CDN$4/t).

Macerated alfalfa harvested in relatively dry field conditions (Falher, Alberta) and processed into pellets had a greater ruminal degradability of DM (56.0 vs. 50.4%) than conventionally conditioned alfalfa pellets (Savoie et al. 1999c). However, macerated alfalfa harvested in a more humid climate (Louiseville, Québec) and processed into cubes showed no statistical difference. Ruminal degradability was 59.4% for macerated cubes and 60.2% for conventionally conditioned alfalfa cubes (Savoie and Tremblay 1998).

**Applied research and development**

A few commercial attempts to develop mower-macerators received some attention in Europe in the early 1990’s (Deutz-Fahr 1993; Krone 1993). Some innovative conditioning devices, based on crushing (i.e. less intensive than maceration but more intensive than conventional roller conditioning) have been reported recently (Hill 1997; McMorran 1999). The list of patents related to intensive forage conditioning clearly indicates commercial interest in developing a system capable of rapid moisture removal and less dependence on weather.

Maceration has been shown to improve the field drying rate and the forage feed value for ruminants in several experiments. However, maceration has also been shown to cause more field losses and reduce forage quality when windrows are subjected to rain, humid conditions, or excessive windrow handling. Forage maceration is therefore a technology most suitable to geographical areas with predictable weather patterns over several days and to livestock operations with high productivity.

Rapid moisture removal without physical damage is achievable with thermal or electromagnetic technologies. Such treatments would reduce the risk of field loss but they would also likely reduce ruminal degradability compared to maceration. The combination of thermal or electromagnetic treatments during harvest with intensive mechanical conditioning at the farmstead just before storage or at the time of feeding could provide the advantages of fast water removal and improved feed value with minimal field loss.

**CONCLUSIONS**

1. Forage maceration has been the object of research at several sites around the world over the last 20 years. It has been shown to considerably improve the field drying rate and reduce respiration loss under ideal drying conditions. Various designs (peripheral rolls, staggered rolls, impact rolls) have been proposed for intensive mechanical conditioning.

2. Maceration can be implemented on various mowers (cutterbar, disk, pull-type, self-propelled). To maintain high mass-flow-rate at the time of mowing, maceration requires additional energy in the order of 2 to 4 kW h/t DM processed.
3. Maceration can improve the feed quality of forages by reducing total respiration and proteolysis, especially under excellent drying conditions where the moisture content declines rapidly. Maceration can, however, reduce the feed quality of forages if it is followed by rain or humid conditions which will extend the period for respiration loss and protease activity.

4. The future of intensive forage conditioning depends partly on further development of a mechanism that is simple enough to maintain low cost of fabrication and operation while still providing the effects of fast drying and improved feed value. Thermal or electromagnetic technologies might in the future represent a useful complement to intensive mechanical conditioning by providing a rapid control of forage moisture while minimizing field loss.

REFERENCES


