Mechanical Maceration of Alfalfa[1]

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ABSTRACT: Maceration is an intensive forage-conditioning process that can increase field drying rates by as much as 300%. Because maceration shreds the forage and reduces its rigidity, improvements in bulk density, silage compaction, and ensiling characteristics have been observed. Macerating forage also increases the surface area available for microbial attachment in the rumen, thereby increasing forage digestibility and animal performance. Feeding trials with sheep have shown increases in DMI of 5 to 31% and increases in DM digestibility of from 14 to 16 percentage units. Lactation studies have demonstrated increases in milk production and BW gain for lactating Holstein cows; however, there is a consistent decrease in milk fat percentage when dairy cattle are fed macerated forage. In vitro studies have shown that maceration decreases lag time associated with NDF digestion and increases rate of NDF digestion. In situ digestibility studies have shown that maceration increases the size of the instantly soluble DM pool and decreases lag time associated with NDF digestion, but it may not consistently alter the rate or extent of DM and NDF digestion.

Key Words: Macerating, Forage, Digestibility, Intake

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Introduction

Mechanical conditioning of forages has been used extensively to reduce drying time before harvest. Decreasing the amount of time that forage lays in the field reduces bleaching and the risk of rain damage, thus providing forage of higher nutritional value. To further enhance drying rate, agricultural engineers have developed the process of maceration to condition forage far more intensively than the mower-conditioners currently in use (Koegel et al., 1988; Kraus et al., 1990). Mechanical conditioning increases drying rate by disrupting the waxy cuticle layer of the plant and by breaking open the stem, thus allowing water to evaporate from the plant without having to diffuse through the epidermis. Maceration intensifies the conditioning by crushing and shredding the stems and homogenizing the leaves and stems, permitting grass and legume forages to dry to 20% moisture in less than 6 h (Shinners et al., 1987; Savoie and Beauregard, 1991) under good drying conditions (Figure 1).

Because the degree of conditioning associated with maceration results in the formation of many small fragments that can fall out of the windrow, macerated forage is pressed into a continuous cohesive strip called a *mat*. For this reason, macerated forage is sometimes referred to as *mat-processed* forage. By equalizing the drying rates of leaves and stems and pressing them together into a mat, the loss of leaves due to overdrying and shattering is virtually eliminated, thus reducing losses of quality and DM during harvest (Koegel et al., 1992). Detailed descriptions of the maceration and mat formation processes, as well as schematic representations of the machinery involved, are available in the literature (Koegel et al., 1988; Kraus et al., 1990; Koegel et al., 1992).

Effects on Physical Properties and Ensilability

In addition to hastening drying rates, the radical change in forage physical structure has shown promise for improving other aspects of forage harvesting, storage, and utilization. Evaluating the effects of maceration on silage production, Shinners et al. (1988) observed that macerated alfalfa compacted to a greater density than unmacerated forage (207.5 vs

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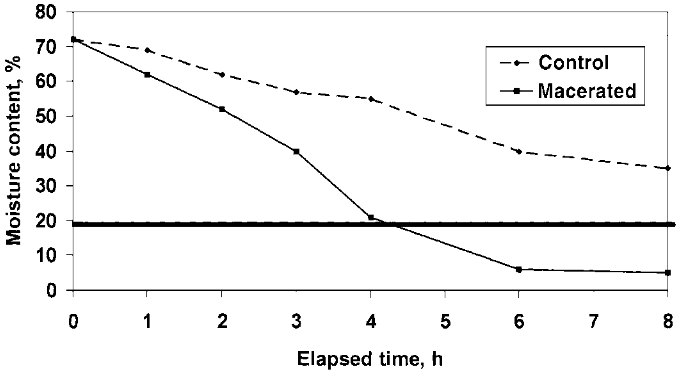

Figure 1. Drying rates for alfalfa swaths with and without maceration (from Shinners et al., 1987).

169.8 kg/m^3 at 55% DM) when subjected to a dynamic load, such as would occur with a tractor packing a horizontal silo. This suggests that macerated silage could be packed to a specific density with less energy expended than required by conventionally processed forage, or, if similarly packed, the greater density of the macerated forage would increase horizontal silo capacity by as much as 20%. When exposed to the dynamic forces present in the chamber of a hay baler, Straub et al. (1989) observed that macerated alfalfa produced bales with 20 to 50% greater DM densities than conventionally processed alfalfa. Increased density would permit a greater amount of hay to be transported in a given load and would thus reduce shipping costs. It is important to note that this research was conducted with small rectangular bales and the density of forage packaged in larger bales has not been evaluated.

When subjected to static load forces, such as would occur during settling in an upright silo, however, Shinners et al. (1988) detected no differences in the final density of macerated and unmacerated alfalfa. They noted that the macerated alfalfa reached its final density faster than the control forage, and this may improve silage quality by providing faster oxygen exclusion and permitting anaerobic fermentation to begin sooner. Faster settling within the silo would also reduce the amount of time required to “top off” the silo, and complete the silo filling process.

In two studies comparing the composition of ensiled alfalfa, Muck et al. (1989) observed significant improvements in silage quality as a result of maceration (Table 1). In both trials, macerated alfalfa had higher concentrations of fermentation products and higher lactic acid bacteria (**LAB**) populations than the control, and macerated alfalfa reached final pH in half the time of the unmacerated alfalfa. Faster fermentation and higher concentrations of end products indicates that the macerated silage would be more stable and less prone to spoilage than the conventionally harvested alfalfa. Because the macerated and control forages had similar sugar and nonstructural carbohydrate levels before ensiling, the higher level of fermentation end products after ensiling suggests that maceration may increase the breakdown of complex carbohydrates or allow a more complete utilization of simple carbohydrates during ensiling. This indicates that maceration could improve the ensiling of forages with low sugar concentrations, a common problem with many forage species.

Muck et al. (1989) also noted that the addition of microbial inoculants did not improve the quality of silage from macerated alfalfa but did increase the fermentation rate and decrease the pH of unmacerated forage. Because of the high level of LAB present in the macerated alfalfa, the authors theorized that much higher inoculant levels would be required to dominate the fermentation of macerated forage and obtain altered fermentation characteristics.

Effects on Digestibility and Animal Performance

Even though limited in number, studies to evaluate the effects of maceration on digestibility and animal

Table 1. Ensiling characteristics of control and mat-processed macerated alfalfa[a]

	Experiment 1			Experiment 2			
Item	Mat	Control	Inoculated control	Mat	Control	Mat	Inoculated control
Dry matter, %	56.2	58.1	57.2	41.5	41.7	40.3	41.7
LAB, log(cfu/g)[b]	4.82^e	2.38^f	3.10^g	7.11^e	4.81^f	7.11^e	4.81^f
pH	4.68^e	5.66^e	4.52^f	5.04^e	5.17^e	5.17^e	4.82^f
TKN, % DM[c]	2.82^e	2.81^e	2.49^f	3.65^g	3.94^{ef}	3.78^{fg}	4.02^e
NPN, % TKN[d]	40.5^e	50.83^f	46.56^{ef}	50.5	46.7	50.3	43.9
Lactic acid, % DM	6.17^e	1.13^f	5.64^e	5.47^e	3.92^g	4.78^f	5.14^{ef}

[a]Data of Muck et al. (1989).
[b]LAB = lactic acid bacteria counts before ensiling.
[c]TKN = total Kjeldahl nitrogen after ensiling.
[d]NPN = nonprotein nitrogen after ensiling.
[e,f,g]Within a row and experiment, means lacking a common superscript letter differ ($P < .05$).

Table 2. Intake and digestibility of control and mat-processed macerated alfalfa fed to sheep[a]

	Experiment 1		Experiment 2	
Item	Macerated	Control	Macerated	Control
Dry matter intake, kg/d	1.22[b]	1.15[c]	1.28	1.22
Apparent DM digestibility, %	58.8	57.2	53.9	51.3
Apparent NDF digestibility, %	48.5[b]	43.0[c]	41.6[b]	35.3[c]
Apparent ADF digestibility, %	50.2[b]	46.0[c]	NR	NR
Apparent CP digestibility, %	70.7	72.1	NR	NR
Ruminal retention time, h	NR[d]	NR	16.9	17.2

[a]Data of Hong et al., 1988a.
[b,c]Within a row and experiment, means lacking a common superscript letter differ ($P < .05$).
[d]NR = not reported.

performance have tended to show beneficial effects. Hong et al. (1988b) observed that maceration of alfalfa increased the attachment of ruminal bacteria during in vitro digestion. Using scanning electron microscopy, the authors observed that maceration of alfalfa plants separated lignified and unlignified cells, significantly increasing the number of adhesion sites available to bacteria. Ruminal bacteria colonized the vascular cell walls of the macerated material to a much greater extent than those of nonmacerated material, increasing in vitro NDF digestion rates for macerated forage to .089 h^{-1} compared with .032 h^{-1} for control forage. Calculations based on these digestion rates determined that 95% of the potentially digestible NDF in macerated alfalfa would be digested in 33.5 h, compared with 94.2 h for the control. The authors concluded that such rapid disappearance of NDF from the rumen would also have beneficial effects on DMI by reducing physical fill limitations.

In a companion study, Hong et al. (1988a) conducted feeding trials with sheep and goats to evaluate the effects of macerating alfalfa hay on animal performance. Even though the macerated alfalfa used in this study was higher in NDF than the control forage, in vivo digestion trials with sheep showed a consistent increase in apparent NDF digestibility and DMI for macerated forage (Table 2). Dry matter and CP digestibilities and passage rates and total tract retention times were not affected by maceration. Ruminal fluid collected 3 h after feeding showed no difference in pH or total or specific VFA concentrations between macerated and control forages. Measurement of particle-associated cellulase activity in situ for the two forages consistently showed higher cellulase activity for macerated alfalfa than the control throughout 48 h of incubation (Hong et al., 1988a).

A trial with early-lactation goats (Hong et al., 1988a) fed a diet containing 60% alfalfa and 40% concentrate showed no difference in milk production as a result of maceration, but DMI and protein percentages were significantly higher for animals fed macerated alfalfa (Table 3). It should be noted that the feeding period for this trial was only 16 d, which may have been too brief to detect milk production differences.

Mertens and Hintz (our unpublished observations) found an increase in DMI, live weight gain, and feed efficiency for macerated alfalfa (Table 4) fed to sheep in digestion crates at ad libitum intakes. The same forage was consumed ad libitum by 12 lactating dairy cattle as part of a mixed diet containing 65% alfalfa (Mertens et al., 1990) in a two-period switchback design experiment with 28-d periods. In this trial, however, no differences in DMI or milk production were observed (Exp. 1, Table 5). It is important to note that in this experiment there was a significant increase in BW for animals fed macerated forage. The animals in this trial were in late lactation and an increase in available energy may have been preferentially partitioned to BW gain instead of milk production. The authors calculated the energy obtained from the forage portion of the diet by summing energy use for milk production, BW change, and maintenance

Table 3. Intake and milk production data for lactating dairy goats fed diets containing 60% alfalfa harvested with and without mat-processed maceration[a]

Item	Macerated	Control	SE
Dry matter intake, kg/d			
Alfalfa	1.54	1.45	.19
Grain	1.04	.99	.13
Total	2.58[c]	2.44[d]	.17
Production			
Milk, kg/d	3.6	3.5	.09
Fat, %	4.01	3.72	.15
4% FCM, kg/d[b]	3.7[c]	3.3[d]	.14
Protein, %	3.00[c]	2.93[d]	.02
Weight change, kg/d	−.13	−.10	.05

[a]Data of Hong et al., 1988a.
[b]FCM = fat corrected milk.
[c,d]Within a row, means lacking a common superscript letter differ ($P < .05$).

Table 4. Intake, digestibility, and performance of control and mat-processed macerated alfalfa fed to sheep[a]

Item	Experiment 1		Experiment 2	
	Macerated	Control	Macerated	Control
Dry matter intake, % BW	4.49[b]	3.42[c]	3.02	2.65
Dry matter digestibility, %	69.2	59.7	NR	NR
Weight gain, g/d	NR[d]	NR	26.3[b]	21.2[c]
Feed efficiency, g gain/kg forage	NR	NR	177	149

[a]Data of Mertens and Hintz (unpublished).
[b,c]Within a row and experiment, means lacking a common superscript letter differ ($P < .05$).
[d]NR = not reported.

requirements and subtracting the energy obtained from the grain that was consumed. Based on these calculations, it was determined that macerated alfalfa provided 1.22 Mcal NE_l/kg of forage consumed, compared with 1.09 Mcal NE_l/kg for unmacerated alfalfa, a 12% increase.

In another study, Mertens and Koegel (1996) fed control or macerated forage harvested either as hay or silage for 7 wk to 48 Holstein cows averaging 80 d in lactation. Diets were balanced to contain 30% NDF and 16% CP and were fed as total mixed rations. Animals fed macerated alfalfa produced more milk but did not have higher DMI than those on control diets (Exp. 2, Table 5). As with the previous study, an increase in energy output at similar intake levels indicated that macerated alfalfa was used more effectively by lactating dairy cows. Macerated and control forages were harvested as both silage and hay; however, no differences that were due to preservation method were observed when comparing the effects of maceration. As with the previous lactation study with dairy cattle (Mertens et al., 1990), there was a significant depression in milk fat percentage for animals fed macerated alfalfa. The depression in milk fat percentage and increased BW gain in these two experiments suggest that ruminal fermentation was shifted toward a lower acetate-to-propionate ratio. However, it is unclear whether this change in pattern of ruminal fermentation was due to a more rapid rate of digestion of the macerated forage or to a reduction in rumination because the physical effectiveness of macerated fiber is reduced. Even though the length of fiber is not affected by maceration, the diameter and strength of the fiber particles is reduced, which may reduce the physical stimulation of the rumen and alter rumination.

A detailed evaluation of rumination and fermentation characteristics was conducted by Mertens et al. (1991) to determine whether the milk fat depression associated with macerated forages was related to changes in ruminal fermentation, and whether changes in chewing activity might explain any changes in fermentation pattern. Four lactating cows equipped with ruminal fistula and averaging 7 wk in lactation were fed total mixed rations containing 60% alfalfa. Milk production did not differ between macerated and control diets (Table 6); however, as with previous studies, milk fat percentage was lower for animals fed the macerated forage. Ruminal pH and total VFA production were similar between macerated and control forages and agree with the observations of Hong et al. (1988a). Contrary to the findings of Hong

Table 5. Intake and performance of lactating dairy cattle fed control and mat-processed macerated alfalfa

Item	Experiment 1[a]		Experiment 2[b]	
	Macerated	Control	Macerated	Control
Dry matter intake, kg/d	19.6	19.9	23.2	23.4
Milk, kg/d	24.2	24.5	37.1[c]	34.5[d]
Fat, %	3.53[c]	3.71[d]	3.37[c]	3.66[d]
4% FCM, kg/d[c]	22.4	23.5	33.5	32.6
Body weight change, kg/d	.44[c]	.08[d]	.09	−.06
NE_l from forage, Mcal/kg	1.22	1.09	NR[f]	NR

[a]Data of Mertens et al. (1990); diets consisted of 65% alfalfa and 35% concentrate.
[b]Data of Mertens and Koegel (1996); averaged over hay and silage preservation methods; diets balanced to contain 30% NDF and 16% CP.
[c]FCM = fat corrected milk.
[d,e]Within a row and experiment, means lacking a common superscript letter differ ($P < .05$).
[f]NR = not reported.

Table 6. Intake, chewing activity, milk production, and ruminal fluid characteristics of lactating dairy cattle fed control or mat-processed macerated alfalfa[a]

Item	Macerated	Control
Dietary NDF, %	26.6	28.4
Dietary CP, %	19.9	18.1
Dry matter intake, kg/d	19.9[b]	21.0[c]
NDF intake, % BW/d	.93[b]	1.03[c]
Milk, kg/d	35.7	35.3
Milk fat, %	2.96	3.20
Milk protein, %	2.92	2.92
Eating, min/d	253[b]	319[c]
Ruminating, min/d	484[b]	520[c]
Chewing/NDF, min/kg	29.0	29.6
Total chewing, min/d	738[b]	840[c]
Ruminal fluid pH	5.80	5.81
Total VFA, m*M*	123	123
Acetate, m*M*	73.7[b]	79.0[c]
Propionate, m*M*	30.7[b]	25.1[c]
Acetate:propionate ratio	2.49[b]	3.26[c]

[a]Data of Mertens et al. (1991).
[b,c]Within a row, means lacking a common superscript letter differ ($P < .05$).

et al. (1988a) there was a change in the proportions of VFA as a result of maceration; macerated forage had significantly greater propionate and less acetate than unmacerated forage. Changes in the acetate-to-propionate ratio of this magnitude are commonly associated with milk fat depression in lactating dairy cattle and probably explain the consistent reduction in milk fat percentage observed in animals fed macerated alfalfa (Santini et al., 1983; Shaver et al., 1986).

Time spent eating, ruminating, and for total chewing was decreased by maceration of alfalfa (Table 6). Part of this reduction can be attributed to the reduced DMI and lower NDF levels of the macerated diets. When compared on the basis of chewing activity per kilogram of NDF, there were no differences between macerated and control alfalfa, indicating that fiber effectiveness of macerated alfalfa is similar to conventionally harvested forage. The decreased total chewing times suggest that the macerated diets may have resulted in less salivary buffer secretion than control diets. However, the 738 min of total chewing per day by the cows that were consuming the macerated forage is close to the 744 min/d suggested by Mertens (1997) to maintain milk fat production of cows in mid-lactation. This suggests that total chewing activity was not limiting when forages were macerated. The lack of difference in ruminal pH between macerated and control treatments also suggests that the effect of maceration on altered fermentation pattern in the rumen is probably not mediated through changes in physical effectiveness of macerated fiber. It seems likely that differences in digestion kinetics are responsible for altered ruminal fermentation when forages are macerated.

Dry matter and NDF intakes were lower for cows fed diets containing macerated alfalfa, even though diets containing macerated forage were slightly lower in NDF than control diets (Table 6). Because similar quantities of milk were produced from smaller quantities of macerated alfalfa, a greater quantity of energy must have been made available owing to maceration. By back-calculating energy obtained from forage, as in a previous study (Mertens et al., 1990), the authors estimated that macerated alfalfa provided 1.47 Mcal NE_l/kg of forage consumed compared with 1.36 Mcal NE_l/kg for the control. This represents an 8% increase in available energy and is comparable to the increase of 12% observed in the previous study. An increase in available energy as a result of maceration could explain why animals fed macerated forage consumed less than those on control diets. If intake is regulated by energy balance and not physical fill, the higher energy available from maceration would result in a decreased intake. If intake is regulated by physical fill and maceration reduces fill by increasing digestion rate, intake would be expected to increase, as has been observed in previous research (Hong et al., 1988a).

In general, feeding trials with macerated alfalfa have shown increases in forage digestibility and utilization, and in most cases an improvement in one or more measures of animal performance. Milk fat depression in lactating animals seems to be a consistent response to consumption of macerated forage, but it is probably due more to an alteration of ruminal fermentation than to a loss of effective fiber. When calculated, a consistent 8 to 10% increase in energy availability resulting from maceration has been observed for dairy cattle. A change in the acetate-to-propionate ratio in favor of propionate is considered desirable in growing and finishing animals, and suggests that further research with feedlot cattle may be justified.

Conditioning Intensity and Forage Digestion

Because maceration is an energy-intensive operation, equipment manufacturers interested in commercializing the technology may wish to decrease the intensity of conditioning as a means of reducing fuel consumption. To determine the possible ramifications of decreasing the intensity of maceration, it is important to be able to accurately measure conditioning intensity and to understand how changes in conditioning may affect animal performance.

In an attempt to develop a standard technique for measuring conditioning intensity, Kraus et al. (1997b) compared surface area index (**SAI**) to leachate conductivity (**LC**) as methods for quantifying extent of conditioning. Because maceration increases the surface area and the leaching of cellular contents, both approaches seemed plausible. Leachate

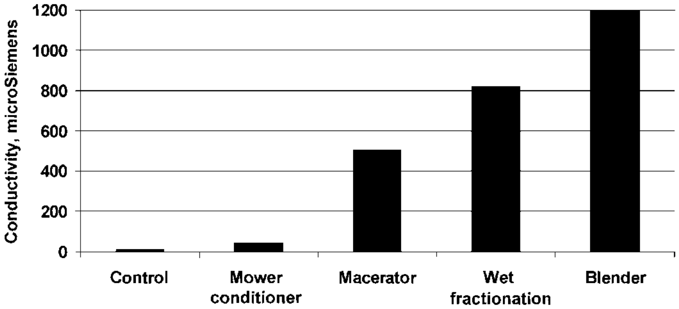

Figure 2. Leachate conductivity of various forage processing methods (from Kraus et al., 1997b).

conductivity, measured as electrical conductivity of an aqueous solution leached from the conditioned forage, was found to be a more sensitive and simpler analysis than SAI. Differences in intensity of conditioning among various implements were easily observed with LC (Figure 2). To simplify comparisons, Kraus et al. (1997b) suggested the use of a conditioning index (**CI**) to quantify the level of cellular disruption. The CI is defined as percentage LC of a treated forage compared with the LC of the same forage processed in a Waring blender for 1 min at a speed of 18,000 rpm. For example, if a treated forage had a LC of 400 μsiemens (**S**)/cm and the blended treatment had a LC of 1,200 μS/cm, the CI would be $(400/1,200) \times 100 = 33$.

Using LC to characterize the intensity of conditioning, Kraus et al. (1997a) compared in situ DM and NDF disappearance of alfalfa harvested with four different conditioning implements. Leachate conductivity and instantly soluble DM increased and NDF digestion lag decreased as the severity of conditioning increased. Unconditioned forage had a LC of 28 μS/cm and a NDF digestion lag of 8.7 h, compared with 60 μS/cm and 4.5 h for forage conditioned with intermeshing rubber rolls, 518 μS/cm and 1.5 h for a crushing-impact macerator, and 992 μS/cm and no lag time for the rotary impact macerator, respectively. Total DM and NDF dissappearance and rates of DM and NDF digestion did not differ among conditioning treatments (Figures 3 and 4); however, instantly soluble DM increased and NDF digestion lag time decreased with increasing severity of conditioning. These findings agree with the work of Hong et al. (1988b) that maceration increases cellular rupture and allows more rapid attachment by ruminal microorganisms, but it does not support their findings of an increase in NDF digestion rate. The reason for this discrepancy is unknown, but it may be related to the fact that only five time points were evaluated by Kraus et al. (1997a). Had a greater number of time points been evaluated, a more sensitive analysis of kinetic parameters would have been possible.

The data of Kraus et al. (1997a) emphasize the importance of characterizing the exact degree of

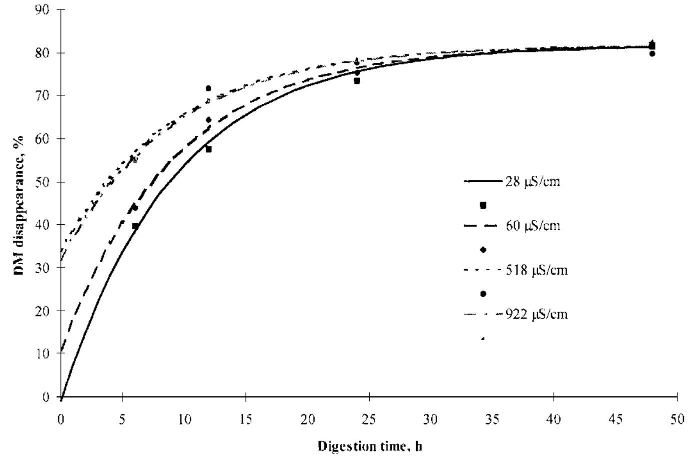

Figure 3. In situ DM disappearance for alfalfa macerated at four intensities (from Kraus et al., 1997a).

conditioning imposed by a specific piece of equipment. Even though two types of macerators were evaluated, the crushing-impact and rotary-impact, the LC and in situ digestion characteristics were significantly different. Because macerators are developed by various manufacturers, they will most likely differ in the maceration technique that they use. If this is the case, it will be important to evaluate their LC or CI values to more accurately predict what effects they will have on animal performance.

Because maceration increases the instantly soluble DM pool and reduces the lag associated with NDF digestion, the greatest benefits in animal performance will be observed for animals with rapid ruminal turnover rates, such as high-producing dairy cattle. However, if maceration does not change the rate or extent of digestion, animals with slow rates of passage from the rumen, such as animals at maintenance levels of intake, will experience few if any nutritional benefits from maceration.

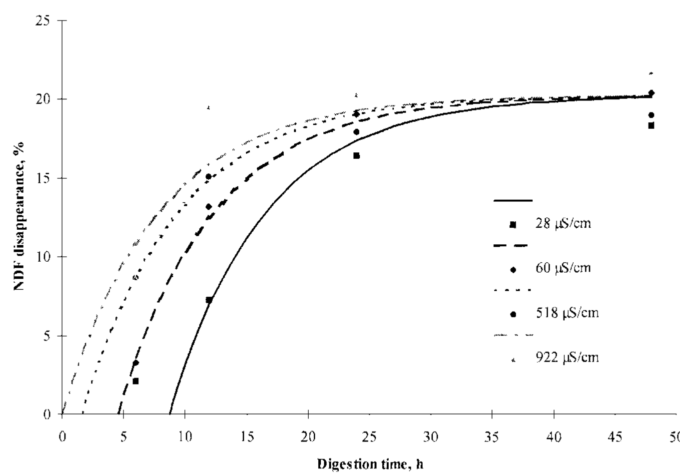

Figure 4. In situ NDF disappearance for alfalfa macerated at four intensities (from Kraus et al., 1997a).

Implications

Maceration of forages significantly increases drying rate, and it may also improve forage density, ensiling characteristics, forage utilization, and animal performance. Even though macerators will probably be more expensive to purchase and operate than conventional harvesting equipment, these added benefits may make them economically feasible. Because machines from various manufacturers are likely to differ in their intensity of maceration, the conditioning index of each machine will need to be determined in order to properly estimate the magnitude of expected differences in animal performance. Based on animal performance trials and in situ studies, it appears that forage destined for use in the diets of feedlot cattle and high-producing dairy cattle will show the greatest increase in animal performance.

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