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RESEARCH CONCERNING MECHANICAL PROCESSING OF NORTH AMERICAN FORAGE CROPS TO ENHANCE FEED VALUE

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ABSTRACT

Mechanical manipulation of forage crops by shredding, lacerating, macerating or processing has been shown to produce improved physical properties for some ruminant feedstuffs. Many benefits arise from the increased specific surface area that result from tearing and shredding the plants stems, leaves and kernels. This disturbance of the physical form can improve field drying, ensilability, rate and extent of fiber digestion, starch utilization and DM intake. Significant value is also apparent through reduced feed sorting, increased compressibility and easier handling.

Greater surface area due to maceration has produced increases in drying rates of 26 to 160% when applied to alfalfa and grass at cutting under North American conditions. Forages treated in this manner have shown increases in 6-h *in situ* DM digestibility of 28 to 40%. *In vivo* trials comparing macerated and control forages showed improved conversion efficiency by producing the same amount of milk using less forage DM or producing more milk with the same DM intake as control treatments. Processed whole-plant corn silage increased milk production and DM intake when dairy cattle were fed roller processed conventional corn hybrids. Typically, milk production increased 4 to 10% and DM intake increased 4 to 11%.

Level of processing are affected by such factors as processor roll clearance, roll speed ratio, machine throughput and number of passes through the processor. Specific energy requirements ranged from 2 to 9 kW•h/t DM for multi-roll macerators processing fresh alfalfa or grass and 0.6 to 1.2 kW•h/t WM for single-nip roll processors processing whole-plant corn silage. These energy requirements are substantial so achieving only the minimum needed level of processing to provide positive economic benefits is important. An important first step is to develop systems and procedures to quantify the processing level. Developed systems have included actual quantification or indices of particle-size, surface area, leachate conductivity, kernel breakage, compressibility and particle specific gravity. Plant particle-size is the most widely used measure and is known to have a significant effect on animal performance and health. In addition, relatively good correlation has been found between a leachate conductivity index and forage DM and NDF digestion. Kernel breakage and particle-size from processed whole-plant corn silage were well correlated with starch utilization.

Research concerning important machine variables, performance parameters and resulting animal performance from roll processing of whole-plant corn silage, macerating of un-wilted alfalfa and roll processing of wilted alfalfa are reviewed. Suggestions for future research in the area of mechanical processing of forage crops are offered.

KEYWORDS. Forage, mechanical-processing, digestibility, animal-performance

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INTRODUCTION

Forages are the most important ruminant animal feedstuff. Mechanisms capable of increasing animal utilization of forages would have a significant economic impact on worldwide production of dairy and meat products. Compared to concentrates, forages are relatively inexpensive to grow, store and feed, yet there is still interest in exploring ways to increase efficiency and throughput to make forages even more economical, thereby positively influencing the producer's profit margin (Minson, 1990; Fahey et al., 1993).

Several routes have been explored in hopes of modifying the digestibility of forages. Research in this area can generally be classified in to three areas (1) genetic, (2) biological/chemical and (3) physical.

Genetic research toward improving forage feed value commonly focuses on reducing plant barriers to digestion, such as lignin content or endosperm thickness, through breeding or genetic mutation (Buxton and Casler, 1993). Introduction of superior digestibility into the plant sometimes results in detrimental side-effects on other characteristics such as winter hardiness (Buxton et al., 1995), disease resistance, stalk strength (Buxton and Casler, 1993) or yield.

Biological and chemical approaches to improved digestibility include the use of white rot fungi, enzymes (Varga and Kolver, 1997; Fahey et al., 1993), sodium hydroxide, ammonia or oxidizing agents to weaken or decay lignocellulosic structures (Minson, 1990), thereby making nutrients more accessible. Use of white rot fungi to reduce the presence of lignocellulosics has provided mixed results but is accompanied by substantial DM loss during storage because of the fungal activity. Ammoniation improved forage digestibility after 72 h digestion (Sirohi et al., 1988), but this improvement is likely of limited value for high producing cows with high rumen turn over rates and forage-rumen residence times ranging from 20 to 30 h (Woodford et al., 1986; Reis and Combs, 2000). Biological and chemical treatments are also suspect due to worries about animal health effects and reduced voluntary intake of treated forages (Weiss et al., 1986).

Because of the challenges and costs associated with genetic, biological or chemical approaches, mechanical processing remains a viable alternative to improving forage digestibility. Research exploring the relationship between physical treatments and animal response are reviewed in this paper. Suggestions for future research to solidify the role mechanical processing in today's harvesting schemes will are provided.

GOALS OF CROP PROCESSING

Modifying the physical characteristics of the plant through mechanical disruption has been referred to as laceration, shredding, maceration, or processing. These processes have the goal of increasing surface area, decreasing stem rigidity and altering particle-size. Each of these factors alone may provide several beneficial effects to aid animal utilization of forages.

Increasing the specific surface area has the effect of increasing field drying rate, ensilability, digestibility and dry matter intake (DMI). Drying coefficients of 20 to 160% better than conventional roll conditioning have been observed when intensive forage conditioning is incorporated into hay cutting (Savoie, 2001). Maceration involves longitudinally cracking the stem and waxy cuticle of the plant (Priepke and Bruhn, 1970; Ajibola et al., 1980; Shinners et al., 1985; Charmely et al., 1997). Silage and hay made of macerated alfalfa has shown qualitative improvement because of decreased time from cutting to storage but also, because of the release of cell contents, increased sugar availability for lactic acid bacteria during ensiling (Muck et al., 1989; Charmely et al., 1999). Digestibility increases have been attributed to creation of more attachment points for rumen microbes and separation of lignified and unlignified cells (Hong et al., 1988a). Both attributes should advantageously affect rate and extent of dry matter (DM) digestion by removing physical barriers to microbial attachment (Buxton and Redfearn, 1997). Hong et al. (1988b) calculated the rumen residence time for 95% neutral detergent fiber (NDF) digestion of macerated alfalfa to be 60 h less than conventionally harvested alfalfa. Several experiments and reports have shown that enhanced NDF digestibility causes increased rumen passage rates and, thus, increased appetite (Oba and Allen, 1999; Reis and Combs, 2000). Some i*n vivo* trials with fresh, macerated forage have shown little improvement in total tract digestibility or milk production while other *in situ* and *in virtro* trials have shown optimistic results (Hong et al., 1988a; Koegel et al., 1992; Mertens and Koegel, 1996). While tract digestibility and milk production have varied, energy balances are usually increased by feeding macerated forage (Koegel et al., 1992; Charmely et al., 1999; Mertens and Koegel, 1996). Trials performed using processed, wilted alfalfa have produced mixed results (Barrington et al., 1971; Shinners et al., 2000b) but concerns exist over the attainable level of processing of wilted alfalfa and the animal response to this treatment.

Processing whole plant corn silage (WPCS) increases feed efficiency by cracking corn kernels and increasing fodder surface area. Increasing kernel specific surface area, thus circumventing the hard endosperm and expediting microbial attachment, has shown total tract starch digestibility improvement of 4 to 6 percentage units (Bal et al, 2000; Johnson et al., 2002), while reducing or eliminating the passage of visible whole kernels in the feces (Moreira et al., 2000; Bal et al., 2000). These digestibility improvements to WPCS have provided improved feed conversion to meat and/or milk (Larsen, 1979; Moriera et al., 2000).

The effects of reduced stem rigidity and component particle-size are closely related. Both effects help reduce sorting (Beardsley, 1964) and improve handling, densification and palatability (Larsen, 1979). Reduced sorting is most commonly seen in processed WPCS where large cob sections are crushed by the processor, and intermingle better with fodder and kernel particles, thereby becoming less sortable (Bal et al., 2000). Reduced stem rigidity improves crop densification in the silo. Increase of initial silo density has been observed for macerated silage, which might produce faster silo settling that allows more timely silo "top off" and increased silo capacity (Shinners et al., 1988b). Faster densification also produces greater oxygen exclusion, thus aiding fermentation (Muck et al., 1989; Charmely et al., 1999).

MECHANISMS FOR PROCESSING

Over the years, numerous ingenious processor designs and innovations have been developed to improve forage properties. The majority of these systems use a multiplicity of longitudinally grooved rolls operating at a small clearance. When combined with a roll tip speed differential (TSD), the small roll clearance has the ability to abrade, crack and shred stems and kernels as they pass through the processor. One of the first processors developed was known as a recutter. It used a stationary screen at the exit of a drum type cutterhead to further break kernels and minimize the presence of large cob sections in feed. Buck et al. (1969) reported power requirements of recutter systems to be three times that of a conventional harvester and also reported some improvement in animal performance when fed re-cut WPCS.

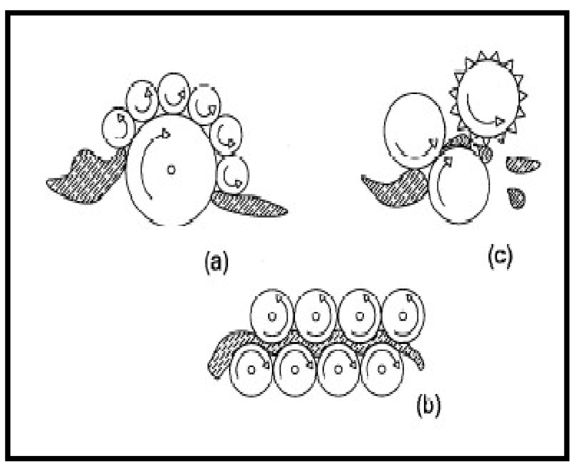

Figure 1: Macerator designs: (a) drum and roll, (b) staggered roll and (c) crushing impact (Savoie, 2001)

Maceration was performed to increase forage drying rate. Fritz (1986), Koegel et al. (1992) and Savoie (2001) have reviewed macerator designs of the last 25 years and identified three designs which have emerged and been more extensively developed. Figure 1 shows the most important types of macerators: drum and roll (Koegel et al., 1988), staggered roll (Savoie and Beauregard, 1991) and crushing-impact (Kraus et al., 1990). An essential step to reduce DM loss after maceration involves pressing the macerated material back together for deposition onto the stubble as a "mat" before drying (Risser et al., 1985; Shinners et al., 1985). Research has shown that a significant portion of the drying and digestion benefits, as well as a significant amount of power requirement, is due to the maceration process (Shinners et al., 1985).

Corn silage processors on forage harvesters are now widely adopted as producers and nutritionists learn the value of processing kernels and disturbing the physical form of the crop fiber (fig. 2). Processing WPCS is generally accomplished through use of a pair of longitudinally grooved rolls rotating at a differential tip speed with a small roll clearance so that processing takes place by both shearing and crushing. Typical roll clearances are 1 to 4 mm and roll speed differentials of 10 to 25%.

Processing wilted alfalfa silage has been attempted with the processor used to treat WPCS because of its presence on the forage harvester. WPCS processors have, however, been found lacking both in their ability to handle significant mass flows and to perform sufficient damage with acceptable power requirements (Roberge et al., 1998; Shinners et al., 2000a). Concerns also exist about the durability of roll processors when rocks and other foreign objects enter the forage stream, as is typically the case with a crop gathered with a windrow pick-up.

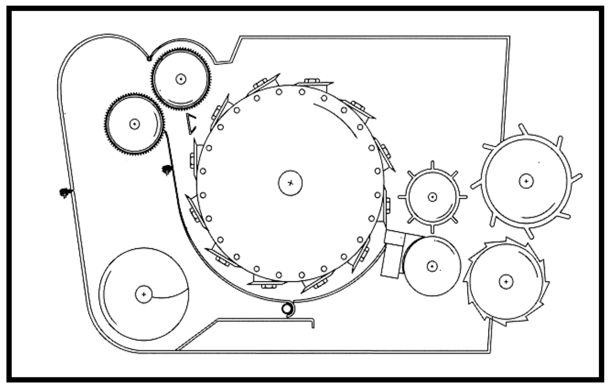

Figure 2: Forage harvester with single-nip crop processing rolls (Shinners et al., 2000a).

PHYSICAL PROPERTIES

Assessment of the physical properties of processed forage crops is important to both researchers and producers. Quantification of processing level by visual inspection is difficult to perform because of observer, operator, machine, and hybrid variability. Certain physical parameters also hold more significance to animal response than others. The most prevalent parameters assessed are whole-plant particle-size (WPPS), surface area index (SAI), leachate conductivity index (LCI), kernel breakage and particle density.

WPPS is assessed through use of a cascading set of oscillating screens to separate the particles by length as per ASAE Standard S424.2 (ASAE, 2002). WPPS has been found to have a significant effect on animal health because an insufficient WPPS will increase incidences of acidosis and laminitis (Oetzel, 2001).

The SAI was developed to determine the relative increase in specific surface area of macerated forages (Shinners et al., 1987). SAI uses the principle that a dried fibrous forage crop with greater surface will re-hydrate more quickly when immersed in water. Attempts were made to correlate SAI to forage drying rate, but the SAI lacked sensitivity, so the LCI was then developed. LCI used the principle that processed and ruptured cells will more readily release their contents when placed into solution, thereby increasing the conductivity of the leachate (Kraus et al., 1997). Indexing is achieved by recording the ratio of sample conductivity to the conductivity of the sample after blending in a household blender. The blending treatment is assumed to have completely broken all cell walls. LCI has been correlated with increased *in situ* DM and NDF disappearance because 60 to 80% of the digestible energy of legumes are stored in the cell content rather than the fiber fraction (Kraus et al., 1997; Buxton and Redfearn, 1997).

Processing WPCS reduced kernel particle-size (KPS), thereby increasing kernel specific surface area (KSSA) and starch digestion (Knowlton, 1998). Questions remain about the appropriate KPS for diary rations (Philippeau et al., 1999). Three methods have been adapted for determination of KPS in WPCS: hand separation, hand separation with correction and hydrodynamic separation. Hand separation requires sorting a sub sample into two fractions, kernel and cob-stover (C-S) (Shinners et al., 2000b). After oven drying the separated kernels, KPS can be determined using the sieving technique as per ASAE Standard S319.3 (ASAE, 1997). Separation of the grain fraction into three sub-fractions; whole, cracked or processed; allows estimation of KSSA using ASAE Standard 319.3 (ASAE, 1997). The corrected hand separation technique takes into account the grain to non-grain dry mass-fraction ratio (K:C-S) present in the standing crop and corrects the hand separated K:C-S ratio to equal the field ratio (Fanning, 2002). Water separation is a new technique that takes advantage of the different buoyancy properties of kernels and C-S. In this method, the whole-plant sub-sample is immersed in water and agitated for several seconds, allowing the grain fraction to settle. The C-S fraction is then skimmed and inspected for errant kernels. The remaining water, kernels and small fiber particles are agitated again. The water and fiber are then poured onto a screen and visually inspected for stray kernels. Kernels remaining in the pan are then oven dried and analyzed as per ASAE Standard 319.3 (ASAE, 1997) for KPS and KSSA. This method has been found to extract very close to all grain fraction present in the WPCS.

Processing forages has the tendency to reduce stem rigidity and increase the ease with which the crop can be compressed (Shinners et al., 1988b). Savoie et al. (1996) used this tendency to develop a method to quantify the relative level of stem processing as a function of compressibility. In this method, a cylinder of known volume was filled with forage and then compressed with a piston. Change in piston height directly indicates change in volume and, thus, compressibility of the forage. Savoie et al. reported a positive correlation between maceration and compressibility, but large variability reduced this parameters effectiveness.

PROCESSING WHOLE PLANT CORN SILAGE

Processor performance is dependant on certain physical characteristics of the system. Johnson et al. (1999) identified 10 significant and 25 secondary factors that should be reported when publishing data about WPCS processing. Other authors agree with this assessment (Roberge et al., 1999; Shinners et al., 2000b) and these factors include crop type, DM, maturity, harvester mass-flow, harvester type and model, processing method, theoretical length of cut (TLC), roll clearance, TSD and roll tooth pitch. All of these factors combine to influence machine performance with respect to power requirements, WPPS, and kernel and fiber physical form.

Table 1: Effect of TLC and processing on kernel damage (from Shinners et al., 2000b)

Processed	TLC mm	Whole kernel fraction % of total mass
No	9.5	33
No	19	42
Yes	19	4

Before processors were used, WPCS was typically cut quite short (9.5 mm TLC) to insure adequate kernel processing with the cutterhead. However, processing can produce significant reduction in the fraction of whole, intact kernels even at long TLC (table 1). For this reason, 19 mm TLC and 3 mm roll clearance is generally recommended for processed WPCS (Shinners et al., 2000b). Processing certainly requires some expenditure of power, but the ability to almost double the TLC from 9.5 to 19 mm allows power saved at the cutterhead to be used by the processor, so the net increase for the forager harvester is only 5 to 10% (Shinners et al., 2000b).

Table 2: DM disappearance of WPCS after 24 h *in situ* (% of total DM) (from Shinners et al., 2000b)

Maturity	Unprocessed	Processed
Early dent	55.9_b	58.4_a
½ Milkline	48.6_d	58.5_a
Black layer	43.6_e	52.2_c

a,b,c,d,e – significantly different at P<0.05

In situ analysis of processed versus unprocessed WPCS revealed increased DM and starch digestibility (Bal et al., 2000; Johnson et al., 1999). Both effects are linked to disruption of the plant physical form and, therefore, increased accessibility of rumen microbes for attachment and colonization. Increases of starch digestibility with processing result from breakage of the kernel endosperm and reduction of KPS, which can mitigate the effect of kernel maturity and vitreousness by breaking the protein matrix present in older, more vitreous kernels (Shinners et al., 2000b; Fanning, 2002).

In vivo animal trails using processed versus unprocessed WPCS have produced varied results but typically have shown processing to be beneficial. Test results with brown-mid-rib hybrids have generally shown little or no advantage to processing (Schwab et al., 2002). Decreased sorting of the cob and long fiber has been observed in processed WPCS at longer TLC (Larsen, 1979; Bal et al., 2000). Enhanced total tract starch and DM digestibility are generally accompanied by increased milk production and depressed milk fat content (Moreira et al., 2000). Fiber digestibility of processed WPCS in the total tract tends to be depressed *in vivo* for reasons that aren't fully understood (Dhiman et al., 2000). Some possible explanations include increased DMI and rate of passage, increased starch digestion, decreased rumen pH, decreased chewing time (which normalizes particle size (Schwab et al. 2002) and decreases buffering of the rumen due to decreased saliva production), or the fact that processed 19 mm TLC is normally compared against 9.5 mm unprocessed and these rations then don't have identical WPPS or long fiber concentration. These uncertainties underscore that further investigation of the animal requirements and silage characteristics are required to correctly balance dairy diets to recognize the full benefits of WPCS processing.

Fresh Forage Maceration

Attempts to improve the ruminant animal utilization of alfalfa and grasses have been conducted since the 1950's and 60's when laceration was assessed in a processor similar to the re-cutter systems for WPCS (Balch et al., 1955; Baxter et al., 1966). Results showed increased power requirements but no positive correlation between plant damage and animal performance. Because of this, limited attempts to process fresh forages were made until the late 1970's when interest in alfalfa fractionation for protein extraction received attention (Lu et al., 1979). One observed side effect of severely treating alfalfa was that the increased surface area had a tendency to increase the rate at which the forage could release moisture. Researchers reported significantly reduced drying time to storage moisture when forages were intensively conditioned, or macerated (Shinners et al., 1985; Savoie and Beauregard, 1991).

Researchers also noted the increased specific surface area of the highly processed material produced significant enhancement of DM and fiber digestibility (Lu et al., 1979; Hong et al., 1988b; Koegel et al., 1992). Measuring the level of processing and relating this measurement to animal performance were considered important. Kraus et al. (1997) found DM and NDF digestibility significantly increased by maceration (fig. 3). The rupture of cells to expose their contents (Buxton and Redfearn, 1997) and separation of lignified and unlignified cells (Hong et al., 1988b) produced this increased digestibility.

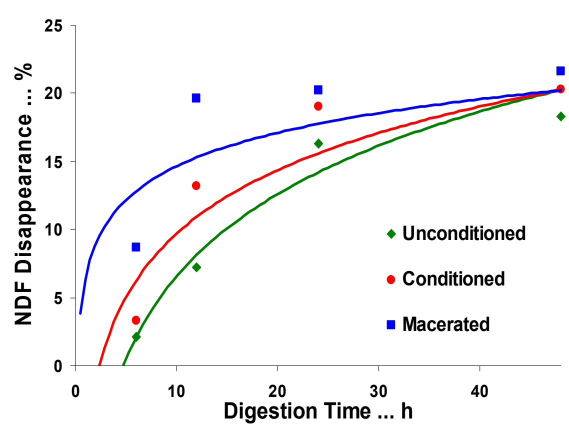

Figure 3: NDF digestion curve of Alfalfa treated to differing levels (Kraus et al., 1997).

Although maceration improved forage drying rate and also improved animal performance, the process has never been commercialized. This could be attributed to the need for further technological developments to reduce losses through pressing, non-uniform material distribution in the mat and magnitude of the capital investment needed to change the entire forage harvesting machinery line-up.

Wilted Forage Processing

Because of the recent rise of interest in processing WPCS, producers and researchers have looked at the feasibility of the roll processor to treat alfalfa at silage harvest. Initial tests showed moderate animal response *in situ* and almost no effect *in vivo* probably because of the inability to significantly process the crop with only one roll nip. In addition, because this crop was processed at moistures below those in standing crop, the ratio of cell wall to cell contents was high, providing increased resistance to physical manipulation. Finally, power requirements were high, especially when low moisture alfalfa tended to accumulate 'gum' in the roll grooves (Shinners et al., 2000a).

Table 3: Processed, wilted alfalfa *in situ* DM disappearance and milk production (from Shinners et al., 2000a)

	TLC	DMd from *in situ* trail	Milk yield from *in vivo* trial
	mm	% of total DM	kg/cow/d
Unprocessed	9.5	55.7	40.5
Processed	19	60.5	40.6

Shinners et al. (2000a) performed a test containing both *in situ* and *in vivo* trials with identical crop. They reported a 5 percentage unit increase of the *in situ* forage DM digestibility (DMd) at 24 h but the *in vivo* trial showed no increase in milk production or dry matter intake (table 3). Roberge et al. (1999) found no increase of overall or effective DM degradability of processed, wilted alfalfa, however they conducted digestibility tests on ground samples which would mask the effects of different processing treatments. Barrington et al. (1971) used a re-cutter to harvest low moisture grass silage and found no digestibility benefits associated to harvesting in this manner.

Digestibility Trial Design

We felt that the digestibility improvement from processing wilted forage needed further investigation. Our test was designed to explore the use LCI as an indicator of cellular damage to predict the expected level of *in situ* digestibility of DM, NDF and acid detergent fiber (ADF) of wilted alfalfa (NDFd and ADFd, respectively). Moisture content at processing was an additional variable. The processing levels were defined as low, medium or high processing and correspond to levels similar to those seen when fresh cut forages have been chopped, processed or macerated, respectively. *In situ* digestibility of DM, NDF and ADF was to be assessed at both 12 and 24 h.

Procedures

Fourth crop alfalfa was cut on September 23rd and 25th, 2002. Crop was acquired by hand at 0, 24, 29, and 52 h after cutting, corresponding to approximately 77, 61, 54 and 43% moisture, respectively. Three processing treatment levels were targeted, low (L) at 10% LCI, moderate (M) at 30% LCI and high (H) at 60% LCI.

All material was first chopped with a lab-scale chopper at 19-mm TLC. After chopping, 1/3 of the material was separated, identified as the L treatment, then sealed in a plastic bag and stored at 5°C. To produce the M treatment, a two-roll processor with 63% TSD was used with wet-mass-flow-rate of 7.4 kg/s/m processor width. To produce the H treatment, a 7-roll macerator, with 6 roll nips set at 0.6 mm roll clearance and 53% TSD was used with wet-mass-flow-rate of 2.0 kg/s/m processor width (Fritz, 1986). After one pass through the either processor, a sub-sample was analyzed to determine if the target LCI had been reached. If the level of processing was insufficient, the material was re-processed until it reached the target LCI. At the high moisture, only one pass was required to reach the target LCI but at the all the other moistures, three passes were required for both the M and H treatments. The samples were packed for ensiling in a mini-silo (102 mm dia x 375 mm PVC). After 54 d the silos were opened and the crop analyzed.

All forages were analyzed for DM, LCI and particle length. DM was determined by oven drying at 103°C for 24 h or 55°C for 72 h for the un-ensiled and ensiled treatments, respectively (ASAE Standard S358.2, ASAE, 2002). LCI analysis was performed on the un-ensiled forage using 5 g DM per sample placed in a 500 mL glass jar with 300 mL distilled water and inverting every 15 s for 2 min. Conductivity of the solution was immediately measured using a DIST 3 Conductivity Probe (temperature compensated, Hanna Instruments). The sample was subsequently treated in an ordinary household blender operating at high speed for 1 min after which conductivity of the blended solution was measured with the same instrument. Measurement of the solution conductivity after blending allowed for calculation of LCI. Particle length of the un-ensiled treatments was determined according to ASAE Standard S424.2 (ASAE, 2002).

In situ analysis of ensiled forage was performed using a macro bag technique. The samples were un-ground forage to preserve physical characteristics and differences between treatments. Dacron® bags (10 cm x 23 cm with 53 μm pore size) were filled with 7.5 g DM and double sealed with a hot wire filament. The *in situ* tests were performed November 19th, 2002. Two ruminally cannulated, multiparous Holstein cows housed at the University of Wisconsin Dairy Cattle Center were used for the *in situ* trial. Cow 3993 averaged 20.4 kg/d milk yield and was at 406 days in milk (DIM) for the trial. Cow 4569 averaged 29.5 kg/d milk yield and was at 249 DIM for the trial. Cows were fed once daily with a diet consisting of 30% alfalfa haylage, 20% WPCS and 50% corn grain.

Bags were placed in triplicate in the rumen for 12 or 24 h. Upon removal from the rumen, all samples were washed and then dried for 48 h at 55°C to determine DM disappearance. Dried samples were then ground through a UDY mill (2 mm screen) and analyzed using wet laboratory techniques for NDF, ADF and protein disappearance (Goering and Van Soest, 1970).

Statistical Analysis

Data were grouped according to digestion time and nutrient component and analyzed as a split-plot design with the SAS Mixed Model Procedure (SAS, 2001). The model for all analyses included the effect of processing level (P), moisture level (M) and the interaction between processing and moisture level (P*M). Random effects were also assigned as cow and cow by bag by time. Effects and interactions were determined significant at $P<0.05$. Levels of significance were assigned within component and time groups if the P*M interaction was significant at $P<0.05$.

Results

Processing and moisture level each significantly affected the physical properties, *in situ* digestibility and storage characteristics of the processed alfalfa silage (tables 4 and 5). The high incidence of the P*M interaction was likely the result of an increasing ratio of cell wall to cell contents as the crop lost turgor while drying and thus processing characteristics were altered. Processing and moisture were significant factors for the majority of the response factors studied.

The sole significant factor in WPPS was the level of processing (table 4). This was expected because of the shredding and comminution caused by the more intensive processing methods. LCI was targeted to be 10, 30 and 60% for L, M and H processing levels, respectively, for all four moisture levels. However, for a given processing level, there were some significant differences between LCI's across the four moisture levels (table 4). Within each moisture level, there was always a significant difference in LCI between processing levels.

Moisture was significantly different between processing levels within each wilting period (table 4). This was likely because of both windrow variability and moisture release during, and immediately after, processing. Attempts were made to minimize these effects by thorough mixing of the samples and hasty storage after processing but moisture released during processing was uncontrollable.

Silage density was not specifically tested because of lack of experimental silo replication but the trend toward increased wet and dry density with processing can be seen (table 4). This trend agreed with previously published data (Shinners et al., 1988; Savoie et al., 1996).

Table 4: Physical characteristics of wilted alfalfa after processing

Wilting period	Processing level	WPPS	LCI[3]	Moisture		Density	
				Into silo	Out of silo	WM	DM
		mm	%	% wb	% w.b.	kg/m^3	kg/m^3
Fresh cut	L	39.4	11.2_a	77.8_i	77.1_g	711	163
	M	24.6	28.4_{cd}	75.9_h	76.0_g	860	206
	H	17.0	56.8_f	76.7_{hi}	75.3_g	941	232
Wilted 24 h	L	52.4	12.7_a	63.2_g	63.1_f	786	290
	M	44.6	31.2_d	60.7_f	61.9_f	824	314
	H	32.4	56.6_f	59.0_e	58.5_e	857	356
Wilted 29 h	L	73.4	14.9_b	54.9_d	51.6_d	747	361
	M	45.6	31.1_{cd}	53.3_d	52.1_d	809	388
	H	18.3	61.5_g	50.5_c	49.3_c	827	419
Wilted 52 h	L	73.8	14.2_{ab}	44.3_b	41.7_b	549	320
	M	49.8	27.7_c	39.7_a	39.6_a	642	388
	H	16.2	51.5_e	44.5_b	42.4_b	672	387
P<[2]	Proc.	***	****	****	**	-	-
	Moisture	ns[1]	****	****	***	-	-
	P*M	ns	***	***	**	-	-

[1]Nonsignificant effect, P>0.05
[2]Levels of significance * P<0.05, ** P<0.01, *** P<0.001, **** P<0.0001
[3]Averages with differing subscripts are significantly different at P<0.05

Data on pH and organic acid contents of the silages (table 5) show trends of decreased pH or increased acid content with processing level. Silage pH was not statistically analyzed but a trend toward decreased pH with increased processing existed, with moisture having the most prominent influence. Processing significantly increased organic acid content for two of the four moisture levels (table 4). The decreased acid content with decreasing moisture agrees with the findings of Muck (1990). An advantage of highly processed wilted forage is that silage fermentation is enhanced, even as crop moisture falls.

The presence of a significant processing effect (P<0.0001) through all digestibility component/time combinations corresponded well with our hypothesis that processing wilted alfalfa would increase rumen utilization. Some caution is appropriate, however, because the use of un-ground forages *in situ* removes mastication and mobilization within the rumen from the digestion process. At 12 h, it was apparent that as moisture decreased, so did DMd for the L and M processing levels (table 5). For the H processing level, DMd was statistically similar for the top three moisture ranges, but DMd did fall at the lowest moisture. Focusing on the last three moisture levels for 12 and 24 h DMd there is evidence of a roughly 4 to 10 percentage unit increase in digestibility from the L to H processing levels. Results at 12 and 24 h of ADFd and NDFd were also quite positive, showing increased digestibility of 9 to 26 percentage units from L to H processing levels. Oba and Allen (1999) analyzed multiple *in vivo* trials and found that, on average, a one percentage unit increase of *in situ* or *in vitro* digestibility resulted in a cow response of +0.17 kg DMI/d and +0.25 kg of 4% fat corrected milk/d.

These results show the benefits to DM and fiber digestion through use of processing wilted alfalfa, especially in the range of moisture commonly used for ensiling. Therefore, processing wilted alfalfa should provide substantial benefits if efficient processing methods are developed and dairy cattle rations are balanced to take advantage of the improved forage characteristics. Based on the results, LCI appears to give a reasonable predictor of the expected forage component digestibility,

Table 5: Alfalfa silage – chemical and digestibility characteristics from *in situ* trial

Field treatment	Processing level	pH	Total VFA	DMd		NDFd		ADFd	
				12 h	24 h	12 h	24 h	12 h	24 h
			% DM	% dry basis					
Fresh cut	L	4.84	11.4_{e}	62.3_{e}	73.0_{de}	3.9_{ab}	23.9_{a}	5.9_{ab}	23.0
	M	4.65	12.5_{ef}	63.3_{e}	72.1_{d}	6.3_{ab}	22.6_{a}	7.7_{b}	22.1
	H	4.42	12.7_{f}	63.2_{e}	75.9_{ef}	8.4_{b}	35.5_{b}	8.6_{bc}	34.9
Wilted 24 h	L	4.63	6.4_{cd}	55.6_{bc}	70.1_{cd}	6.2_{ab}	28.6_{ab}	6.6_{ab}	26.6
	M	4.54	5.1_{c}	59.0_{d}	72.7_{de}	4.1_{ab}	28.3_{ab}	8.0_{b}	30.7
	H	4.58	6.9_{d}	60.3_{de}	74.5_{e}	11.7_{bc}	37.9_{bc}	13.6_{c}	36.7
Wilted 29 h	L	5.73	0.6_{a}	53.4_{b}	68.7_{bc}	1.8_{a}	26.2_{ab}	1.2_{a}	23.9
	M	4.73	2.3_{b}	57.2_{cd}	74.1_{e}	4.5_{a}	32.4_{b}	4.3_{ab}	29.2
	H	4.74	4.4_{c}	62.6_{e}	78.8_{f}	22.3_{d}	52.1_{d}	18.1_{c}	47.8
Wilted 52 h	L	5.82	0.3_{a}	47.1_{a}	64.7_{a}	1.3_{a}	25.7_{ab}	2.9_{ab}	23.6
	M	5.68	0.2_{a}	49.4_{a}	65.5_{ab}	17.4_{cd}	35.5_{b}	14.6_{c}	30.0
	H	5.49	0.8_{a}	56.5_{cd}	71.2_{cd}	21.2_{d}	44.4_{c}	16.6_{c}	39.3
P<[2]	Proc	-	****	****	****	****	****	****	****
	Moisture	-	****	****	****	***	****	ns[1]	*
	P*M	-	**	**	*	****	*	***	ns

[1]Nonsignificant effect, P>0.05
[2]Levels of significance * P<0.05, ** P<0.01, *** P<0.001, **** P<0.0001
[3]Averages with differing subscripts are significantly different at P<0.05

FUTURE RESEARCH AND SUMMARY

Recent research efforts have focused on developing mechanical processing systems, using these systems to process forage and finally determining if any animal utilization benefits from processing result. A better approach would involve developing a good understanding of the physical attributes of the forage required by the ruminant animal for optimal utilization. Understanding of these requirements through additional research of rumen microbial reaction to physical form and structure will allow engineers to develop mechanical processing systems to achieve the target physical attributes.

In parallel with this research, further advances in mechanical processing systems are required. Processing wilted forage to achieve a desired physical form at the expense of high power requirements and lower machine throughput are unacceptable. The mechanical systems must be compliant to foreign objects commonly found in crops gathered from a windrow, such as rocks or metal. A technique that can overcome some of these concerns is to process post-ensiling. Ensiled material is often softer and more compliant for a variety of physical and chemical reasons. Therefore, greater improvement in specific surface area per unit energy expended might be expected compared to processing at harvest. The mass-flow through a post-ensiling processor would be much less than at the harvester so more effective processing could result. However, the benefits of improved ensilability would be lost by post-ensiling processing.

Separation of WPCS into grain and non-grain streams at harvest is worthy of study. If processing the non-grain fiber fraction in a single-nip roll set does not improve the digestibility of the fiber fraction, then it might be wise to eliminate processing this fraction altogether or to develop alternative processing devices for this fraction. About half the mass of WPCS is non-grain, so omitting this fraction would improve machine capacity and reduce power requirements. Power would be expended only to process the kernel and cob to break the endosperm and combat maturity and vitreousness through KPS modification. Alternatively, different mechanical processing systems for the non-grain fraction could be developed that are not as power intensive as a single-nip roll set. In either case, it could be envisioned that once the harvester separates the crop into grain and non-grain fractions, the two steams could be merged prior to ensiling or the fractions could be ensiled separately and re-mixed at feeding. The latter scenario would allow for custom blending of the energy and fiber fractions of WPCS for animals of different production capability.

CONCLUSIONS

- Processing whole-plant corn silage has led to improvements in starch utilization and DM digestibility by ruminant animals that generally improve forage conversion to milk. Processing whole-plant corn silage is now widely practiced in North America.
- Maceration of fresh alfalfa has produced faster field dry-down and greater forage digestibility, but the lack of commercially available systems to macerate forage has prevented these benefits from being realized.
- Processing wilted alfalfa significantly improved DM and fiber digestion and enhanced fermentation properties. For producers to realize the benefits of processing wilted forage, further research is required to identify the optimum physical form for ruminant digestion and to develop mechanical systems to provide this physical form.

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