IMPROVING ALFALFA FIBER DIGESTION THROUGH EXTREME MECHANICAL PROCESSING

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ABSTRACT

An intensive form of mechanical processing was investigated to improve alfalfa feed value. This process ruptures cells and increases surface area for microbial attachment in the rumen, facilitating greater fiber digestion. Shredding and impact processing were investigated with the latter process creating more favorable physical properties. During *in situ* digestion experiments, processing significantly increased the rapidly soluble fraction and the rate of DM and NDF degradation of wilted alfalfa. A 6-week dairy lactation trial with 36 cows compared the effect of two identical diets (30% alfalfa haylage, 30% corn silage and 40% concentrates) where the haylage was either conventionally chopped (CON) or chopped and then mechanically processed (MP). Cows fed the MP diet tended to have less DMI (27.3 vs 28.0 kg/d; P=0.09) than cows fed the CON diet. Milk yield was not significantly different between treatments (46.1 (CON) vs. 46.8 (MP) kg/d; P=0.22), however, milk fat percentage for cows fed the MP diet was greater than cows fed the CON diet (3.94% vs. 3.81% fat; P=0.02). Because of greater fat percentage, fat-corrected milk for cows fed the MP diet was greater than cows fed the CON diet (46.2 vs. 44.8 kg/d, P=0.03). Feed conversion efficiency, defined as FCM/DMI was greater for cows fed the MP diet compared to cows fed the CON diet (1.69 vs 1.60, P=0.003). Estimated income over feed costs remained greater for the MP diet despite the added cost to process alfalfa haylage. Overall, cows fed the MP diet were more efficient and out-performed cows fed the CON diet.

INTRODUCTION

Alfalfa digestibility is typically managed with harvest maturity but there is a trade-off between maturity and yield. Weather related harvest delays can quickly reduce alfalfa fiber digestibility (Palmonari et al., 2014). Mature fiber is harder to digest, which can have negative effect on milk production. A one-unit increase in forage NDF digestibility (NDFD) was associated with 0.17 and 0.25 kg/d increases in DMI and milk production, respectively (Oba and Allen, 1999). For this reason, extensive efforts have been made to enhance alfalfa fiber digestibility by way of mechanical processing, genetic modification, chemical application, and biological treatment (Adesogan et al., 2019). Our research focused on a novel intensive mechanical processing technique applied at the time of harvest as a method to improve fiber digestibility.

The physical disruption of alfalfa by applying a form intensive mechanical processing known as maceration has been extensively researched (Bacon and Shinners, 2003; Savoie, 2003). The level of fiberization and cell rupture is greatest when maceration was applied at high moisture (i.e., at cutting) when the plant cells are turgid and the stem mechanical strength at its weakest (Shinners et al., 1988; Bacon and Shinners, 2003). Macerating fresh alfalfa increased the rate of microbial colonization of stems and the rate and extent of NDF digestion during ruminal in vitro incubations (Hong et al., 1988a). In several lactation studies macerating fresh alfalfa increased milk yield (Hong et al., 1988b; Mertens and Koegel, 1996; Broderick et al., 1999). Mertens and Koegel (1996) suggested that the combination of lower DM intake with increased milk production was the result of greater energy utilization of macerated alfalfa.

Intensive mechanical processing after field wilting and immediately after chopping has been investigated as an alternative method to mechanically improve alfalfa digestibility. Shredding wilted alfalfa with forage harvester crop processing rolls led to greater *in situ* dry matter (DM) digestion however, the degree of processing was not enough to positively affect dairy cow milk production (Shinners et al., 2000). Both shredding and impact processing of wilted alfalfa was investigated with impact processing more effective at breaking down plant structure than shredding alone (Pintens, 2021). Processing wilted alfalfa by impact significantly increased the rapidly soluble fraction and the rate of DM and pdNDF degradation during *in situ* experiments (Pintens, 2021).

Recognizing the need to maintain adequate particle-size after processing, a processing technique was developed that employed chopping at much longer theoretical-length-of-cut (TLOC) than is conventionally practiced followed by processing by shredding and impact in a modified hammermill, termed the impact-shredding processor (ISPr). The processing action of the ISPr demonstrated its utility to increase the specific surface area of crop material, while maintaining fiber length such that 45% to 60% of the material was greater than 6 mm long (Pintens, 2021).

OBJECTIVES

Our hypothesis was that processing wilted alfalfa with the ISPr would improve performance of lactating dairy cows because of improved fiber digestion in the rumen. Our objective and corresponding results were:

Project objectives:	Project results:
1. To develop an impact-shredding processor that was capable of processing wilted alfalfa to a processing level index (PLI) of at least 70%.	1. An impacts-shredding processor was developed that produced a PLI of 74%.
2. To process and ensile and conserve wilted alfalfa to support a lactation feeding trial.	2. Over 16 metric tons of wilted alfalfa were processed and successfully conserved for the lactation feeding trial.
3. To examine the effects of mechanical processing wilted alfalfa on forage particle-size, feeding behavior, feed intake, and lactation performance of lactating dairy cows.	3. Dairy cows fed a diet of processed alfalfa produced 1.4 kg/day (3.1 lb./day) greater fat-corrected milk while consuming less DM so that feed efficiency was improved.
4. To estimate the economic potential of the MP system through a partial budget analysis.	4. The income over feed costs were greater for the MP diet even when cost to harvest alfalfa haylage was 1.25 to 1.40 times greater than that for the conventionally harvested material.

MATERIALS AND METHODS

Experimental Processor

Previous research showed that processing through a combination of impact and shredding was more effective at producing the desired physical properties than by shredding alone (Pintens, 2021). Therefore, a hammermill was modified so processing took place primarily as the result of impact between the rapidly moving hammers, but some additional attrition occurred by shredding (fig. 1). The novel aspect of this processor was the replacement of the typical hammermill perforated screen with a non-perforated steel scroll with a roughened surface that promoted shredding rather than cutting. Crop material was deposited tangentially into the path of the hammers and was then dragged along an arc of 180 degrees before exiting tangentially. The experimental impact-shredding processor (ISPr) consisted of a 49.5 cm wide rotor with three rows of 22 free swinging hammers per row. Each hammer was 4 mm thick, and they were spaced 19 mm apart. The tip of each hammer was 12.5 mm from the center of its pivot and the traced radius of the hammers was 25 cm. Clearance between the tip of the hammers and the scroll was 10 mm. The tip speed of the hammers was 80 m s^{-1}. The ISPr rotor was powered by a John Deere (Moline, IL) model 6195R tractor through a belt drive that increased speed from 1000 rev min^{-1} to 3056 rev min^{-1} at the rotor.

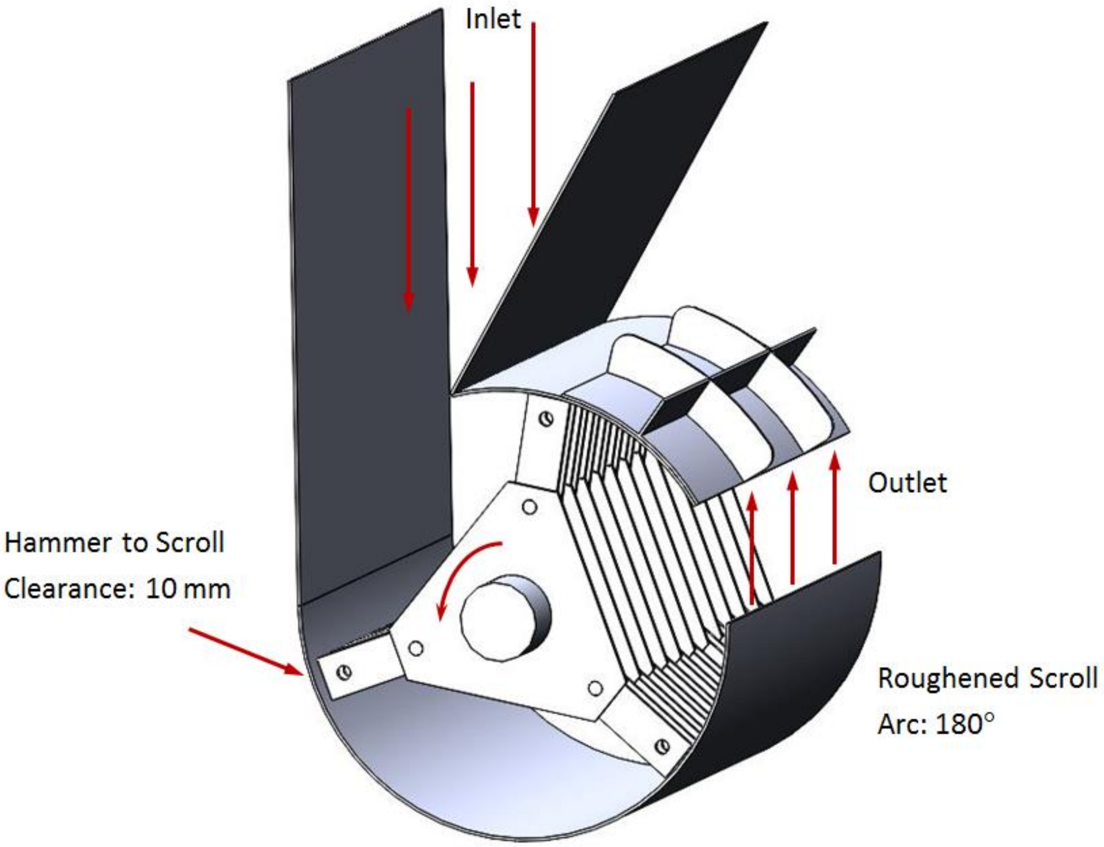

Figure 1. Schematic of impact-shredding processor (ISPr). Note that the scroll was not perforated but rather had a textured, roughened surface.

Forage Preparation for Lactation Experiment

The second cutting alfalfa for both the control (CON) and mechanically processed (MP) diets was harvested at the U.S. Dairy Forage Research Center in Prairie Du Sac, WI. Both treatments came from the same field (Dairyland Magna 100 RR planted in August 2019) and was harvested at late bud maturity 30 or 31 days after first cutting. The CON alfalfa, along with half of the MP alfalfa was cut on June 30th and chopped July 1, 2020 with a Case IH (Racine, WI) model FHX 300 forage harvester. The remaining MP alfalfa was cut July 1 and chopped Thursday July 2. The time required for processing necessitated the two-day harvest of MP alfalfa.

The CON and MP treatments were chopped at theoretical-length-of-cut (TLOC) of 10 and 22 mm, respectively. A longer TLOC was used for the MP material because subsequent processing reduced its particle-size. A total of four and five loads of CON and MP, respectively, were harvested which corresponded to approximately 9000 kg DM of each material. After the MP material was chopped each load was processed with the ISPr using three consecutive passes through the machine. Three passes were required to reach the desired level of processing as quantified by a processing level index (see below). Both treatments were stored in a 2.4 m diameter silo-bag using an Ag-Bag (Eden, WI) model G6060 bagger. As both treatments entered the silo-bag, an inoculant (Biotal Buchneri 500, Lallemand Animal Nutrition, Milwaukee, WI) was applied at the rate of 5 x 10^5 CFU/g of forage. The CON material was bagged first and then MP material completed the bag.

Random samples were collected from each load to determine moisture content, particle-size, and processing level. From these samples, a total of four sub-samples per load of both materials were collected to determine moisture content by oven drying at 105°C for 24 h in accordance with ASABE Standard S358.3 (2017). An additional sub-sample of approximately 6 L was collected per load to determine whole-plant geometric-mean-particle-size (GMPS) using procedures described in ASABE Standard S424.1 (2017).

Processing level was quantified by a processing level index (PLI) which is defined as the ratio of treatment leachate conductivity (LC) relative to that of an ultimate treatment (Kraus et al., 1997a). The hypothesis of this approach was that as processing intensity increases, both the specific surface area and the level of cell rupture also increase, allowing more ions to be released into the leachate (Kraus et al., 1997a). To determine LC, a microwave oven was first used to determine DM content using procedures described in ASABE Standard S358.3 (2017). The calculated DM was used to determine the wet mass needed to create 5 g DM sub-samples, which were placed into individual 600 mL glass containers and 300 mL of distilled water added. The mixture was then shaken for 1 min on an orbital shaker table operated at 180 cycles min^{-1}. The contents were then filtered through two layers of cheesecloth and the conductivity of the leachate immediately measured using a Thomas Scientific (Swedesboro, NJ) model 4366 conductivity meter. Two duplicate samples per load of both CON and MP alfalfas were processed in this manner. A normalizing treatment (n = 4) of pureed material was created by processing the mixture in a Vanaheim (City of Industry, CA) model KB64 blender for 1 min at no-load speed of 28,000 rpm. The pureed material represented an ultimate level of cell rupture. Using this treatment, a processing level index (PLI) was defined as the ratio of the treatment LC_{tr} to the blender treatment LC_{bl}, expressed as a percent:

$$PLI(\%) = \left(\frac{LC_{tr}}{LC_{bl}}\right) \cdot 100 \qquad [1]$$

Kraus et al. (1997b) showed that the relationship between PLI and DM disappearance of macerated fresh alfalfa reached an asymptote occurring at approximately 60% PLI. A PLI of at least 70% was targeted in our research so that the level of fiberization and cell rupture would be slightly greater than that which had previously shown positive animal response.

Experimental Design, Cows, and Diets

The lactation study began after approximately 16 weeks of storage. The study required forty-two lactating Holstein cows, twenty-eight multiparous and fourteen primiparous. Thirty-six of the cows (119 ± 17 DIM) were assigned to either the CON or the MP diet in a randomized complete block design. The remaining six cows were ruminally cannulated and these cows were assigned treatments according to a Latin square design with three-week periods to evaluate the effect of forage processing on ruminal measures. All animal use followed protocols approved by the University of Wisconsin-Madison Institutional Animal Care and Use Committee.

There was a two-week common feeding period, where all cows were fed the herd diet and a baseline for intake and production was established. The diet during the covariate was 26.9% alfalfa silage, 31.6% corn silage, 21.3% high moisture corn, 10.2% canola meal, 7.5% roasted soybeans and 2.5% vitamin and mineral mix (DM basis). Following the two-week covariate was a six-week experimental period. The two treatment diets were identical, except for the alfalfa harvest techniques, described previously (table 1 and 2). Feeding of the covariate diet began on October 22, 2020. Cows were transitioned to their respective treatment diets on Friday, November 6 with each experimental week running from Friday through Thursday. Cows were housed in a tie-stall barn and bedded with chopped straw. They were milked three times daily at 0430, 1130, and 1915 h and fed TMR, ad libitum, after the morning milking.

Each day during the week, random samples of the alfalfa silages, corn silage, high moisture corn and the TMRs were collected and frozen. Once per week samples of the canola meal, roasted soybeans and soybean hulls were collected. Samples were thawed and mixed before sub-samples were collected to determine moisture content by oven drying at 105°C for 24 h. Another sub-sample was oven dried at 55°C for 48 h to be ground for compositional analysis. Additional samples of the alfalfa silages, corn silage and TMRs were taken to determine geometric mean particle-size (GMPS) using procedures described in ASABE Standard

S424.1 (2017). Additionally, fractionation of the TMR samples was done each week using the Penn State Particle Separator (PSPS) (Kononoff et al., 2003).

Forage samples for compositional analysis were ground to pass through a 1 mm screen in a Willey mill (A. H. Thomas Scientific, Swedesboro, NJ). Concentrates were ground through a 1 mm screen in a cross-beater mill (Model SK 100, Retsch GmbH and Co. KG, Haan, Germany). After grinding, samples were composited equally by mass for two-week intervals, leaving three samples for each feed over the six-week treatment period. Ground samples were sent to Rock River Laboratory, Inc, Watertown, WI for wet chemistry analysis of common nutritional composition.

Table 1. Ingredient and nutrient composition of experimental diets (DM basis).

	Treatment diets	
Ingredient composition[1] (% of DM)	CON[2]	MP[3]
CON alfalfa silage[2]	30.0	-
MP alfalfa silage[3]	-	30.0
BMR corn silage	30.0	30.0
High moisture corn	20.0	20.0
Canola meal	8.0	8.0
Roasted soybeans	4.0	4.0
Soybean hulls	5.5	5.5
Mineral and vitamin mix[4]	2.5	2.5
Nutrient composition[5, 6] (% of DM)		
DM[7]	44.0	43.9
CP	17.0	16.7
aNDF	29.0	29.3
Forage NDF	21.0	21.4
ADF	21.1	21.4
ADICP	1.27	1.30
NDICP	0.56	0.61
Lignin	3.60	3.77
Starch	27.3	27.2
NFC	42.4	42.3
EE	3.74	3.77
Ash	8.49	8.49
TDN[8]	72.0	71.7
NE_L[8] (Mcal/kg)	1.70	1.69
Ca	0.86	0.88
P	0.36	0.36
Mg	0.35	0.35
K	1.55	1.52
S	0.24	0.23
RDP balance[9] (g/d)	651	581
RUP balance[9] (g/d)	-402	-420
MP balance[9] (g/d)	-304	-318

1 Percentage of ingredient on a dry matter basis, based on NRC Predictions.

2 Harvested with a forage harvester at 10 mm theoretical-length-of-cut.

3 Harvested with a forage harvester at 22 mm theoretical-length-of-cut before being processed three times in the impact-shredding processor.

4 Mineral and vitamin mix contained (on a DM basis): 16.0% Ca, 5.85% Mg, 0.54% K, 14.8% Na, 6.67% Cl, 0.73% S, 42.5 mg of Co/kg, 519 mg of Cu/kg, 60.2 mg of I/kg, 778 mg of Fe/kg, 2,601 mg of Mn/kg, 14.6 mg of Se/kg, 2,808 mg of Zn/kg, 292 kIU of vitamin A/kg, 58.5 kIU of vitamin D/kg, 1.36 kIU of vitamin E/kg, and 0.494 g of monensin/kg (Vita Plus Corporation, Madison, WI).

5 Values based on average of 3 composite samples, each composite sample represents a 2 week period

6 Wet chemistry analysis done by Rock River Labs, Watertown, WI

7 Average over 6-week treatment period

8 NRC 2001 value

9 Post-trial values calculated using NRC (2001)

Table 2. Nutrient composition of individual diet components.

Nutrient (% of DM)	Diet components[1, 2]						
	Alfalfa silage[3, 4]						
	CON	MP	Corn silage	High moisture corn	Canola meal	Roasted soybeans	Soybean hulls
DM[5]	31.8	30.3	36.9	76.0	88.5	94.1	89.5
CP	26.0	24.9	6.96	7.35	43.3	39.1	11.1
aNDF	37.4	38.6	32.7	7.09	30.1	12.6	65.7
ADF	32.0	33.0	20.0	2.74	23.0	8.55	50.2
ADICP	0.44	0.44	0.05	0.01	1.28	0.30	0.53
NDICP	0.73	0.89	0.14	0.03	2.10	0.40	2.02
Lignin	6.72	7.28	1.21	0.60	11.48	0.93	2.70
Starch	0.40	0.17	41.0	73.8	0.60	0.53	0.41
NFC	22.2	22.0	54.1	80.8	16.9	22.2	19.1
EE	3.20	3.29	2.90	3.30	3.76	21.0	1.43
Ash	12.04	12.03	3.49	1.51	8.03	5.57	4.78
TDN[6]	60.3	59.4	78.2	88.7	63.1	105.8	63.3
NE_L[6, 7]	1.52	1.50	1.66	1.86	1.72	2.60	1.41
Ca	1.11	1.12	0.12	0.01	0.68	0.21	0.56
P	0.39	0.38	0.20	0.30	1.18	0.61	0.10
Mg	0.28	0.29	0.11	0.09	0.55	0.23	0.31
K	3.48	3.39	0.69	0.37	1.07	1.73	0.99
S	0.34	0.31	0.09	0.09	0.71	0.26	0.11

[1] Values based on average of 3 composite samples, each composite sample represents a 2-week period.

[2] Wet chemistry analysis done by Rock River Labs, Watertown, WI.

[3] Control (CON) harvested with a forage harvester at 10 mm theoretical-length-of-cut.

[4] Mechanically processed (MP) harvested with a forage harvester at 22 mm theoretical-length-of-cut before being processed three times in the impact-shredding processor.

[5] Average over 6-week treatment period.

[6] NRC 2001 value

[7] Mcal/kg

Milk Sampling and Analyses

Milk weights were collected at each milking and averaged by week. On Monday and Tuesday of each week, milk samples were collected at each milking that were then analyzed for butterfat, protein, lactose, solids not fat (SNF), milk urea nitrogen (MUN), and somatic cell count (SCC) by AgSource Milk Analysis Laboratories (Menomonie, WI). Composition of the solids was measured using a Foss Milkoscan FT+ and SCC was measured with a Foss Fossomatic FC. Milk composition for a given treatment week was determined by a weighted average based on milk yield at each milking and the duration of the period between milkings.

Animal Behavior

Feeding behavior was monitored for two 24 h periods, 30-Nov. (week 4) and 10-Dec. (week 5). Behavior was observed by five trained observers (~5 h/evaluator) who recorded observations at 5-min intervals. Observations were defined as standing or laying; and either eating, ruminating, drinking, or idle. Eating events were recorded any time a cow was observed eating, consecutive observations were considered one event. Ruminating events were determined to be at least two consecutive observations of the behavior. The total time spent for each behavior was calculated by the sum of the 5-min intervals. Chewing time was the sum of eating and ruminating observations. Time spent chewing per unit of intake (DM and NDF) were calculated using the individual cow DMI for the week the observations were taken.

Statistical Analysis

Data were analyzed using the MIXED procedure of SAS (ver. 9.4, SAS Institute Inc., Cary, NC) utilizing a randomized complete block design with a 2-wk covariate period. Means of intake, milk production, and milk composition were analyzed using the following model:

$$Yijkl = Cov + T_i + W_j + Pk + B_l + (T \times W)_{ij} + (T \times P)_{ik} + (W \times P)_{jk} + (T \times W \times P)_{ijk} + \varepsilon_{ijkl} \quad [2]$$

where Yijkl = dependent variable, Cov = effect of covariate, T_i = effect of treatment, W_j = effect of week, P*k* is the effect of parity, B_l = effect of block, $(T \times W)_{ij}$ = interaction between treatment *i* and week *j*, $(T \times P)_{ik}$ = interaction of treatment *j* and parity *k*, $(W \times P)_{jk}$ = interaction of week *j* and parity *k*, $(T \times W \times P)_{ijk}$ = interaction of treatment *i*, week *j* and parity *k*, and ε_{ijkl} = residual error. Block was treated as a random variable. Week was used as a repeated measure with the covariance structure chosen using the smallest Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The model for BW, BCS, and rumination was analyzed using the same model as describe above but without covariate, week, and all interactions with week. Data were reported as least square means and the Tukey's test was used for separation of treatment means. Interactions with $P > 0.10$ were sequentially removed from the model. Statistical significance and tendencies were defined as $P \leq 0.05$ and $0.05 < P \leq 0.10$, respectively.

RESULTS

Processing with the ISPr created significant physical disruption to the alfalfa (fig. 2). The PLI was 34.8 percentage points greater for the MP material (table 3). The PLI for the MP alfalfa was 51.4%, 65.1% and 72.7% after one, two and three passes through the ISPr. The longer initial TLOC of the MP material (22 vs. 10 mm) helped produce final alfalfa particle-size similar to the CON treatment (8.3 vs. 9.1 mm, $P = 0.052$) as quantified using the ASABE Standard separator (table 3). When the TMRs were fractioned with the PSPS, the CON diet had greater mass fraction longer than 8 mm, and the pef and pdNDF of the CON TMR were greater (table 4).

Table 3. Material properties of alfalfa silages. Processing level index and DM content measured at harvest. Particle-size measured at feeding.

Alfalfa silage treatment	Dry matter content[1] (%)	Processing level index[2] (%)	Geometric mean particle-size[3] (mm)	Fraction of mass[4] (% as-fed)		
				> 19 mm	> 12 mm	> 6 mm
CON[5]	33.7	37.9	9.1	2.0	15.8	60.5
MP[6]	31.6	72.7	8.3	1.5	14.0	56.2
SEM	5.6	0.47	0.27	0.38	1.28	1.31
P-value[7]	< 0.0001	< 0.0001	0.0519	0.3670	0.3245	0.0317

[1] Dry matter content of alfalfa at harvest.

[2] Processing level index of alfalfas at harvest based on treatment leachate conductivity - see equation no. 1.

[3] Geometric mean particle-size of silages at feeding based on screening following ASABE Standard S424.1.

[4] Fraction of mass of silages at feeding residing on top three screens of ASABE S424.1 screener.

[5] Control (CON) harvested with a forage harvester at 10 mm theoretical-length-of-cut.

[6] Mechanically processed (MP) harvested with a forage harvester at 22 mm theoretical-length-of-cut before being processed three times in the impact-shredding processor.

[7] Statistical significance defined as $P < 0.05$, trends defined as $P < 0.10$.

Figure 2. Example of chopped material (right) and processed material (left). Note that processing shreds and fiberizes the stems.

Table 4. Particle distribution of TMR treatment diets using the Penn State Particle Separator (PSPS).

	Treatment diets			
Item	CON[1]	MP[2]	SEM	P-value[3]
PSPS Distribution, (% as-fed)				
> 19 mm	3.37	2.59	0.26	0.047
8 - 19 mm	42.2	38.2	0.50	< 0.001
4 - 8 mm	19.5	21.1	0.29	0.001
1.2 - 4 mm	22.6	26.0	0.28	< 0.001
Bottom Pan	12.3	12.1	0.40	0.728
$\mathrm{pef}_{ps\text{-}2s}$[4]	45.6	40.8	0.53	< 0.001
$\mathrm{pef}_{ps\text{-}3s}$[4]	65.1	61.9	0.54	< 0.001
PSPS Distribution[5], (% DM)				
> 19 mm	2.80	2.00	0.21	0.014
8 - 19 mm	36.6	33.6	0.49	< 0.001
4 - 8 mm	20.7	22.5	0.31	0.001
1.2 - 4 mm	24.8	27.5	0.28	< 0.001
Bottom Pan	15.0	14.4	0.45	0.322
$\mathrm{pef}_{ps\text{-}2s}$[4]	39.4	35.7	0.50	< 0.001
$\mathrm{pef}_{ps\text{-}3s}$[4]	60.2	58.1	0.55	0.016
$\mathrm{peNDF}_{ps\text{-}2s}$[6]	11.4	10.5	0.14	< 0.001
$\mathrm{peNDF}_{ps\text{-}3s}$[6]	17.4	17.1	0.15	0.088

[1] Control (CON) harvested with a forage harvester at 10 mm theoretical-length-of-cut.

[2] Mechanically processed (MP) harvested with a forage harvester at 22 mm theoretical-length-of-cut before being processed three times in the impact-shredding processor.

[3] Statistical significance defined as $P < 0.05$, trend defined as $P < 0.10$.

[4] Material separated in as-fed form, dry matter determined for each sieve and applied for DM distribution.

[5] Physical effectiveness factor (pef) defined as the fraction of particles retained by specific sieves. pefps-2s is the fraction of material retained by the 8 and 19 mm sieves, pefps-3s is the fraction of material retained by the 4, 8 and 19 mm sieves

[6] Physically effective NDF (peNDF) defined as the NDF content multiplied by the fraction of DM retained by specific sieves. peNDFps-2s is the NDF retained by the 8 and 19 mm sieves as a percent of the total DM, peNDFps-3s is the NDF retained by the 4, 8 and 19 mm sieves as a percent of the total DM.

Cows fed the MP diet tended to have less DMI (27.3 vs 28.0 kg/d; P=0.09) than cows fed the CON diet (table 5). After an adjustment period where the intake was more variable, cattle consumed statistically less DM on the MP diet (fig. 3). There were no differences in body weight or body condition score (table 5).

<u>Table 5.</u> Covariate adjusted effects of dietary treatment on intake, BW and BCS.

	Treatment diets			
	CON	MP	SEM	P-value[1]
Item, Intake[2] (kg/d)				
DM	28.0	27.3	0.40	0.09
NDF	8.12	8.02	0.12	0.40
fNDF	5.89	5.85	0.08	0.62
Item				
Initial BW[4] (kg)	644	638	12.5	0.74
Final BW[4] (kg)	665	661	13.0	0.82
Change in BW[4] (kg/d)	0.50	0.55	0.09	0.75
Initial BCS[5]	3.13	3.12	0.07	0.94
Final BCS[5]	3.17	3.18	0.07	0.97
Change in BCS[5]	0.04	0.05	0.02	0.65

1 Control (CON) harvested with a forage harvester at 10 mm theoretical-length-of-cut.

2 Mechanically processed (MP) harvested with a forage harvester at 22 mm theoretical-length-of-cut before being processed three times in the impact-shredding processor.

3 Statistical significance defined as $P < 0.05$, trend defined as $P < 0.10$.

4 Body weight (BW).

5 Body condition score (BCS).

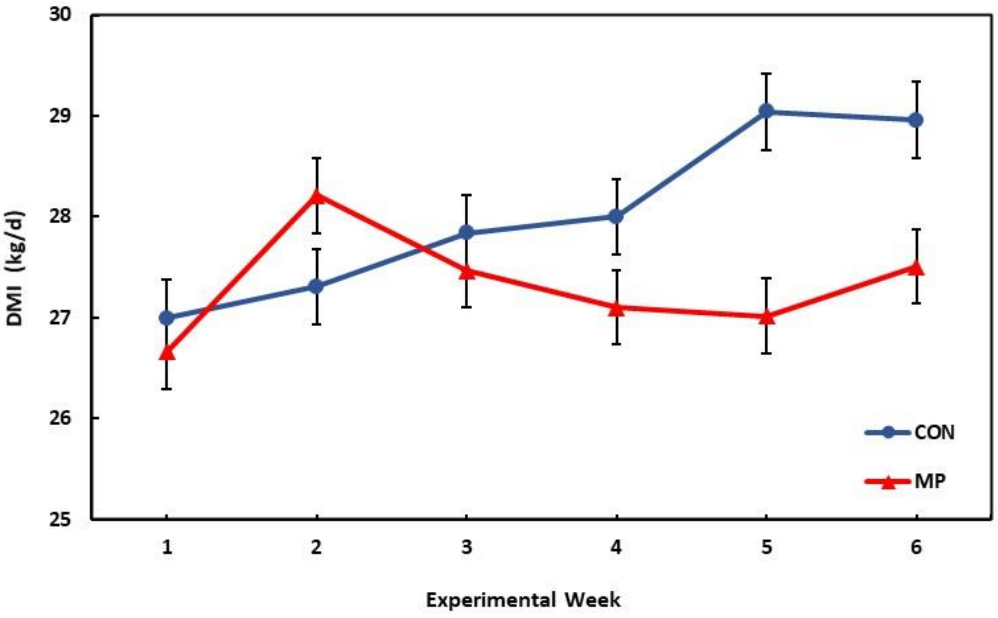

Figure 3. Dry matter intake (DMI) for cattle consuming control (CON) and mechanically processed (MP) diets over the 6-week experimental period. Treatment effect P = 0.0866. Treatment x week effect P < 0.0001.

Although the cows eating the MP diet had slightly lower DMI, milk production was not statistically different (46.1 vs. 46.8 kg/d; P=0.22) (table 6). However, cattle fed the MP diet had statistically greater fat content (3.94% vs 3.81%, P=0.02) and greater total solids (12.91% vs 12.76%, P=0.04) (table 6, fig. 4). Based on the greater fat production, the FCM and ECM were 1.4 kg/d greater with the MP diet compared to the CON diet [46.2 vs. 44.8 kg/d (P=0.03) and 49.5 vs. 48.1 kg/d (P=0.04), respectively]. The combined effect of lower DMI and greater FCM and ECM production led to a better feed efficiency for the MP diet (fig. 5). Feed conversion efficiency, defined as either FCM/DMI or ECM/DMI, was greater for cows fed the MP diet compared to cows fed the CON diet [1.69 vs 1.60 (P=0.003) and 1.81 vs 1.72 (P=0.003), respectively].

Table 6. Effect of alfalfa haylage processing on the performance of dairy cows.

Item	Treatment diets CON[1]	 MP[2]	SEM	P-value[3]
Milk Production				
Milk (kg/d)	46.1	46.8	0.57	0.22
FCM[4] (kg/d)	44.8	46.2	0.59	0.03
ECM[5] (kg/d)	48.1	49.5	0.62	0.04
Milk Composition				
Fat (%)	3.81	3.94	0.05	0.02
Fat (kg/d)	1.75	1.83	0.03	0.01
Protein (%)	3.09	3.10	0.02	0.40
Protein (kg/d)	1.42	1.45	0.02	0.22
Lactose (%)	4.82	4.80	0.01	0.15
Lactose (kg/d)	2.22	2.25	0.03	0.28
TS (%)	12.8	12.9	0.07	0.04
TS (kg/d)	5.89	6.02	0.07	0.09
MUN[6]	12.1	11.9	0.21	0.28
SCC x1,000	106.3	192.4	84.3	0.31
SCS	3.96	4.13	0.17	0.33
Feed Efficiency				
FCM FE[7, 8]	1.60	1.69	0.03	0.003
ECM FE[8, 9]	1.72	1.81	0.03	0.003

[1] Control (CON) harvested with a forage harvester at 10 mm theoretical-length-of-cut.

[2] Mechanically processed (MP) harvested with a forage harvester at 22 mm theoretical-length-of-cut before being processed three times in the impact-shredding processor.

[3] Statistical significance defined as $P<0.05$, trend defined as $P<0.10$.

[4] FCM = [0.4 x milk yield (kg)] + [15 x fat yield (kg)].

[5] ECM = [0.327 x milk yield (kg)] + [12.95 x fat yield (kg)] + [7.2 x protein yield (kg)].

[6] Statistical trend for treatment x week effect ($P<0.10$).

[7] Feed efficiency (FE) = (FCM/DMI).

[8] Statistically significant treatment x week effect ($P<0.05$).

[9] Feed efficiency (FE) = (ECM/DMI).

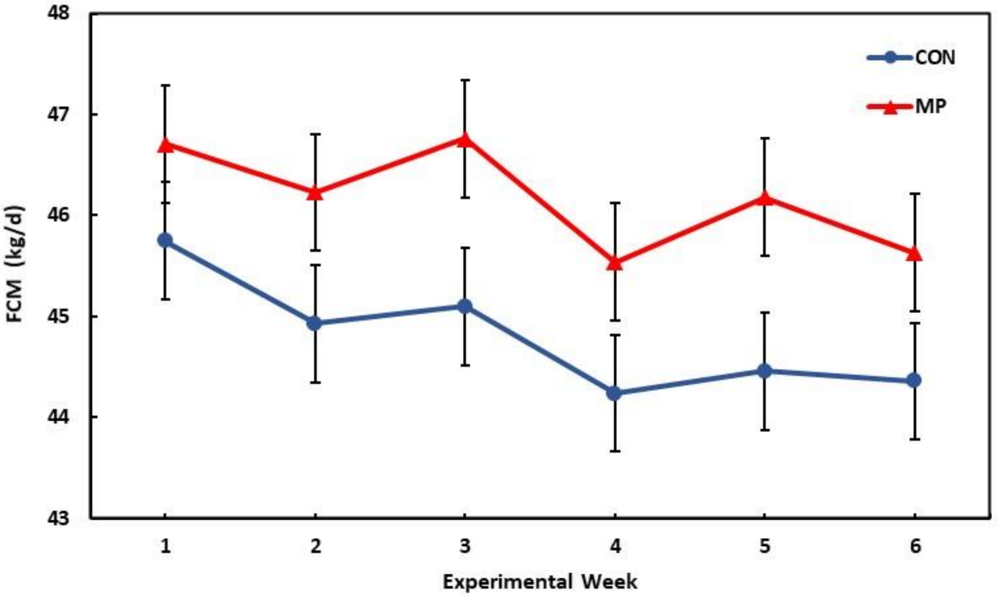

Figure 4. Fat corrected milk (FCM) for cattle consuming control (CON) and mechanically processed (MP) diets over the 6-week experimental period. Treatment effect P = 0.0033. Treatment x week effect P < 0.0001.

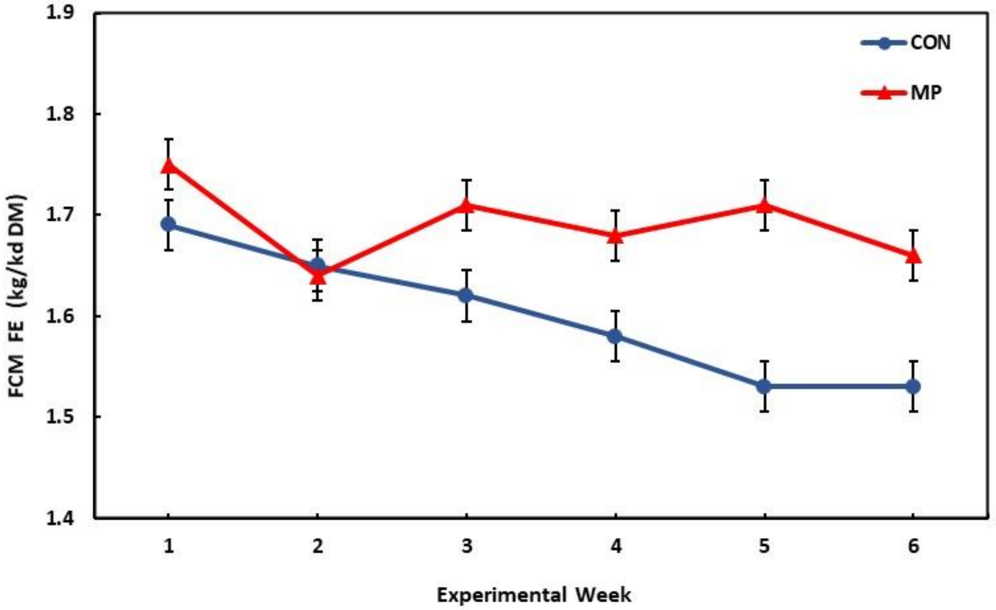

Figure 5. Feed efficiency (FE = FCM/DMI) for cattle consuming control (CON) and mechanically processed (MP) diets over the 6-week experimental period. Treatment effect P = 0.0032. Treatment x week effect P < 0.0001.

Chewing, eating and rumination time was similar for both treatments (table 7). Standing time was less for cows on the MP diet (538 vs. 595 min/d; P = 0.05) and laying time was greater (903 vs. 845 min/d; P = 0.04). The times spent on eating, ruminating, and chewing per kg of DMI and NDF intake were similar for both treatments.

DISCUSSION

Processing resulted in greater cell rupture and surface area as quantified by the significantly greater PLI of the MP material. There was no significant difference in particle-size between the alfalfa portion of the diets. Based on these metrics, the substantive physical difference between the CON and MP alfalfas was the degree of fiberization and cell rupture of MP material rather than differences in particle-size. Particle-size, pef, and pdNDF of the MP diet were slightly less than the CON. Because of the compliant and fiberized nature of the MP alfalfa, it may not have been necessary to mix the MP for the same duration as the CON diet and this may have contributed to greater size-reduction of the MP diet.

Maceration of fresh alfalfa increased extent and rate of disappearance of NDF during in vitro incubation (Hong et al., 1989a). Maceration separated of lignified and unlignified cells as determined by scanning electron microscopy (SEM). Macerated alfalfa stems examined by SEM following *in vitro* incubation showed more extensive bacterial colonization of the cell walls than the control. Disruption of the cellular structure of forage by processing reduced the degree of crystallinity or rigidity of physical barriers which consequently increased digestibility (Lu et al., 1980; Koegel et al, 1973). Maceration of fresh alfalfa increased DM and NDF digestion because of these physical changes (Sirohi et al., 1988; Petit et al. 1994).

Processing wilted alfalfa after wilting is less effective than macerating fresh alfalfa because cells are less turgid and the crop gains mechanical strength as it dries. The PLI was 87% and 65% when the DM content of alfalfa was 20% and 34%, respectively (Pintens, 2021). However, wilted alfalfa at 38% DM and processed to a PLI of 66% had greater rapidly soluble fraction and the rate of DM and pdNDF degradation was increased during in situ experiments (Pintens, 2021).

Animal behavior was observed during weeks 4 and 5 when DMI was statistically less for cows on the MP diet (fig. 3). The MP diet had statistically lower pef and $peNDF_{ps\text{-}2s}$ (table 4). These results are likely reasons why the eating, chewing, or rumination time these values were all numerically less for cows fed the MP diet (table 7). This observation is consistent with those summarized in Grant and Ferraretto (2018).

ECONOMIC IMPLICATIONS

The only difference between the two diets fed was the alfalfa haylage. The energy requirements for chopping and then processing wilted alfalfa haylage was approximately 1.7 to 2.1 times that of conventionally harvested haylage (Pintens, 2021). Current custom rates for harvesting alfalfa haylage (chopping only) are approximately $7 per ton (Iowa Custom Rate Guide, 2021). An economic analysis was conducted assuming the diet used, and lactation results, found in this research (Appendices B and C). It was assumed that cows fed the MP diet would have the improved feed efficiency found here so that less feed was needed for the same milk production as the CON diet. Assumptions used in the harvesting system cost analysis are listed in Appendix B. In this analysis, the cost to harvest wilted alfalfa using the MP system were 1.22 to 1.45 times that of the CON (Appendix C).

The income over feed costs (IOFC) was greater for the MP diet even when cost to harvest alfalfa haylage was greater than that for the conventionally harvested material (fig. 6). In this scenario, a 500-cow herd would have $45,500 to $48,900 greater annual income over feed costs. The results show that for the feed efficiency results found in this research, IOFC is insensitive to the additional costs associated with owning and operating a forage harvester with a MP system. Although new economic analysis will be needed as more knowledge is gained about the costs and benefits of the MP system, current results show the economic benefits outweigh the costs.

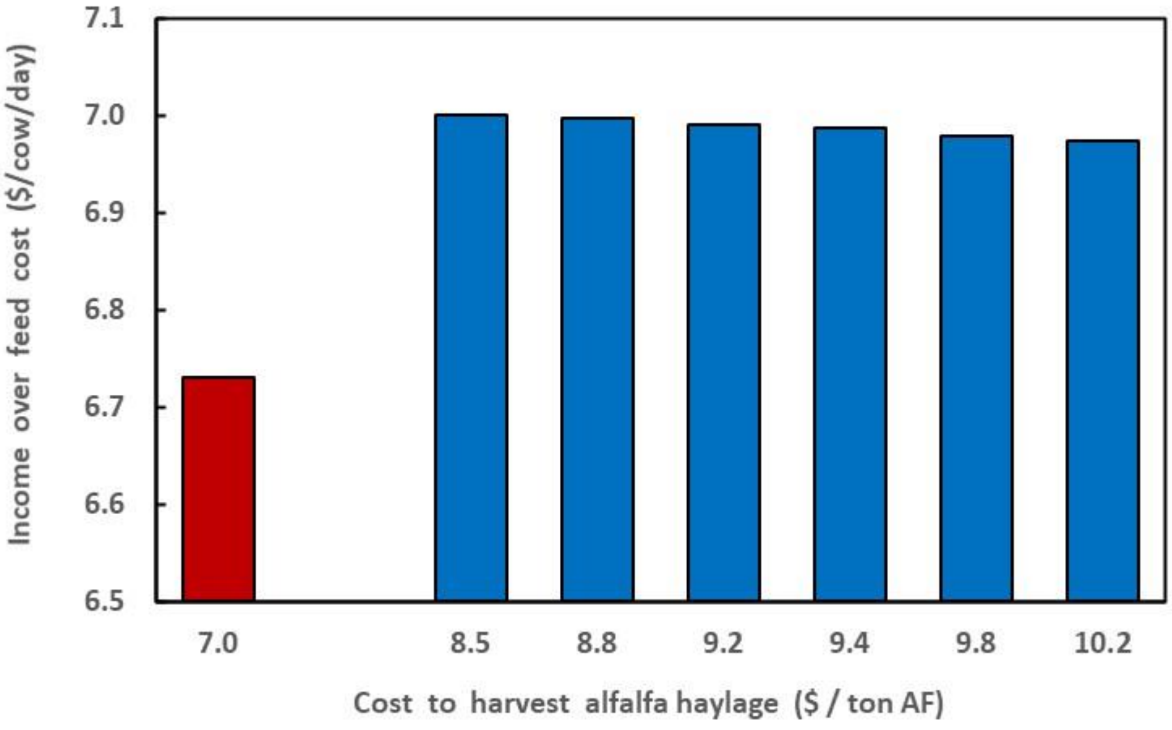

Figure 6. Income over feed costs as impacted by harvest costs for herd feed diet using conventional (red) or mechanically processed (blue) alfalfa haylage.

CONCLUSIONS

Mechanically processing alfalfa through a screenless hammermill caused significant physical disruption to the crop material. The physical disruption was a result of impact and shredding by the hammers and increased processing level, as measured by the PLI. The processing reduced particle-size, but an acceptable fraction of the material was still greater than 6 mm length. When it was incorporated in the diet, processed alfalfa led to lower dry matter intake, greater fat content and greater fat-corrected milk production. The combined effect resulted in greater feed efficiency for cows fed the diet containing mechanically processed alfalfa. Since the diets were the same, except for alfalfa harvest techniques, no significant differences in dietary composition or nutrient intake were noticed. The resulting improvement in dairy cattle lactation performance more than offset the added cost of harvesting with the MP system.

ACKNOWLEDGEMENTS:

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APPENDIX A

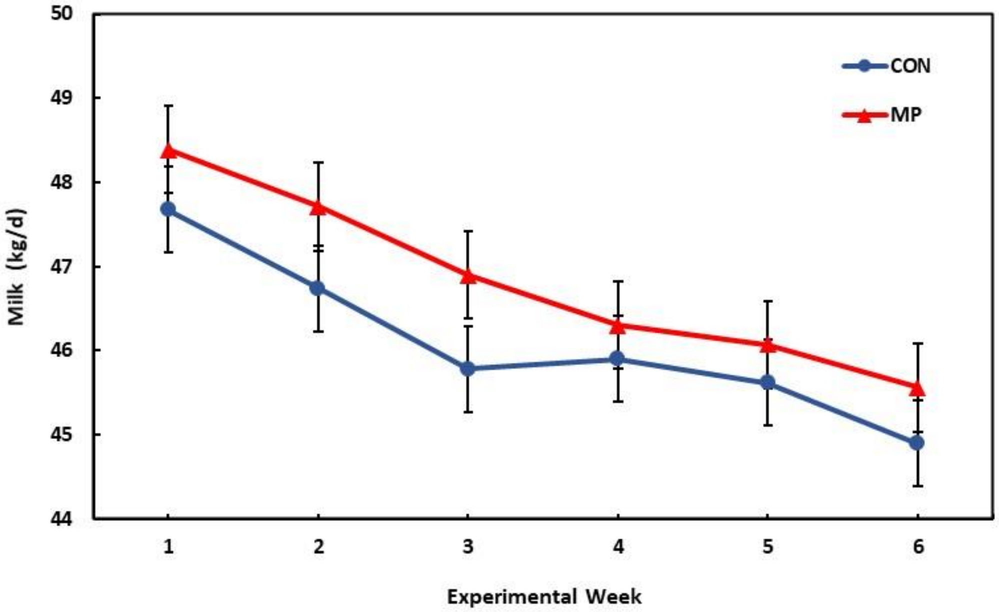


Figure A1. Milk production for cattle consuming control (CON) and mechanically processed (MP) diets over the 6-week experimental period. Treatment effect P = 0.2156. Treatment x week effect P = 0.8791.

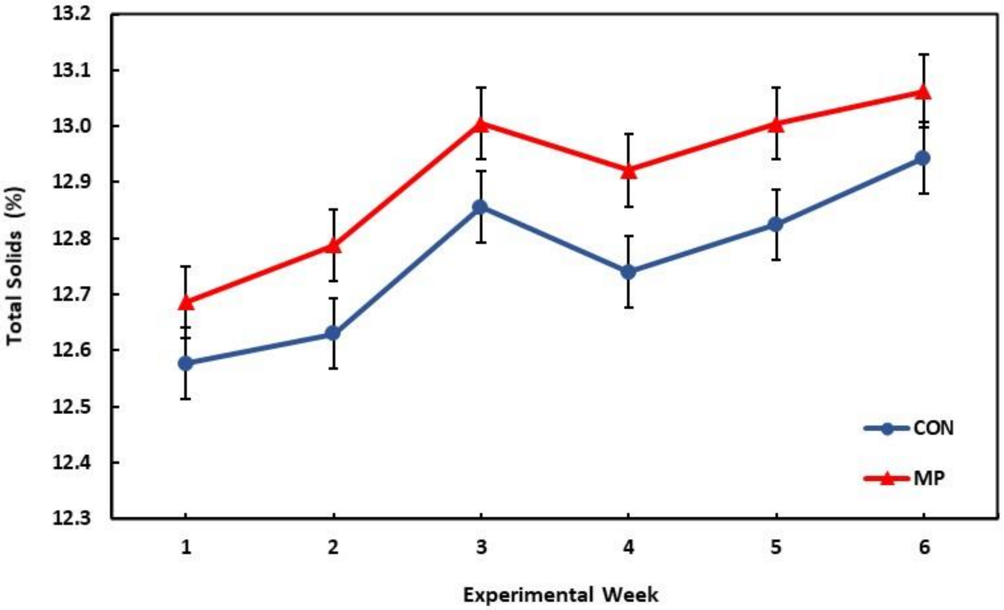


Figure A2. Total solids production for cattle consuming control (CON) and mechanically processed (MP) diets over the 6-week experimental period. Treatment effect P = 0.0401. Treatment x week effect P = 0.9498.

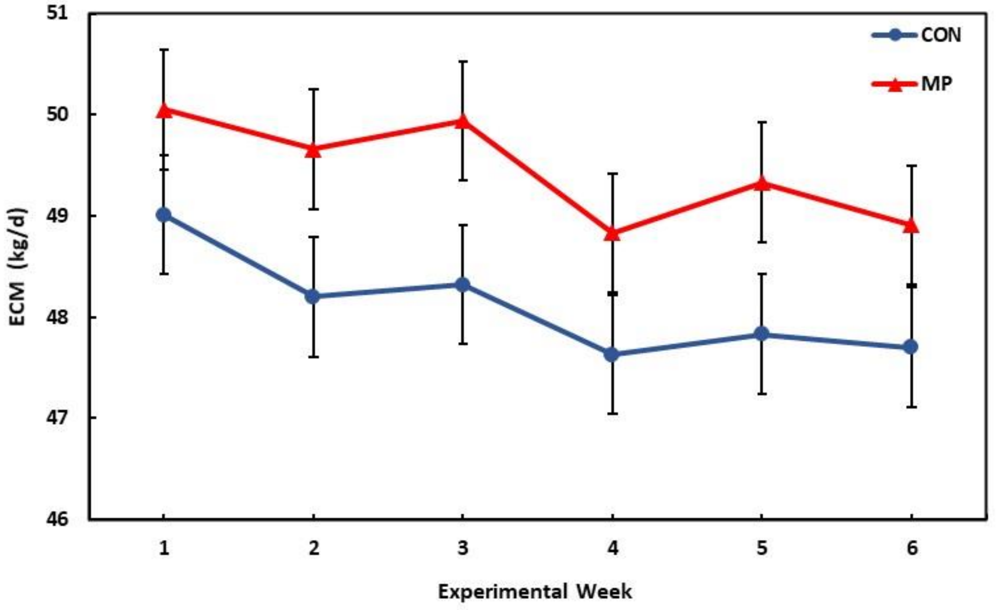


Figure A3. Energy corrected milk (ECM) for cattle consuming control (CON) and mechanically processed (MP) diets over the 6-week experimental period. Treatment effect P = 0.0386. Treatment x week effect P = 0.9826.

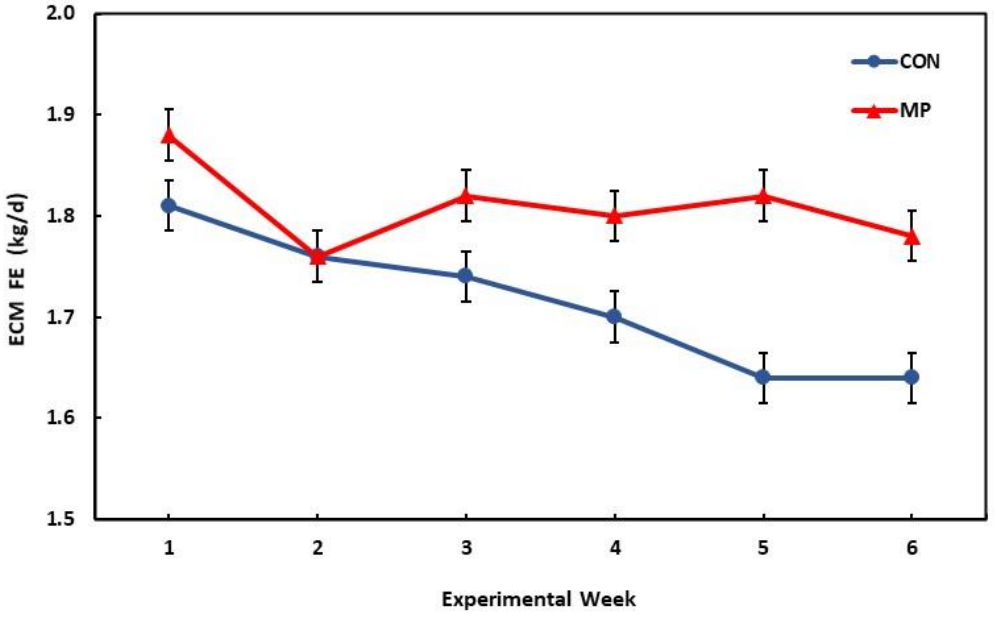


Figure A4. Feed efficiency (FE = ECM/DMI) for cattle consuming control (CON) and mechanically processed (MP) diets over the 6-week experimental period. Treatment effect P = 0.0032. Treatment x week effect P < 0.0001.

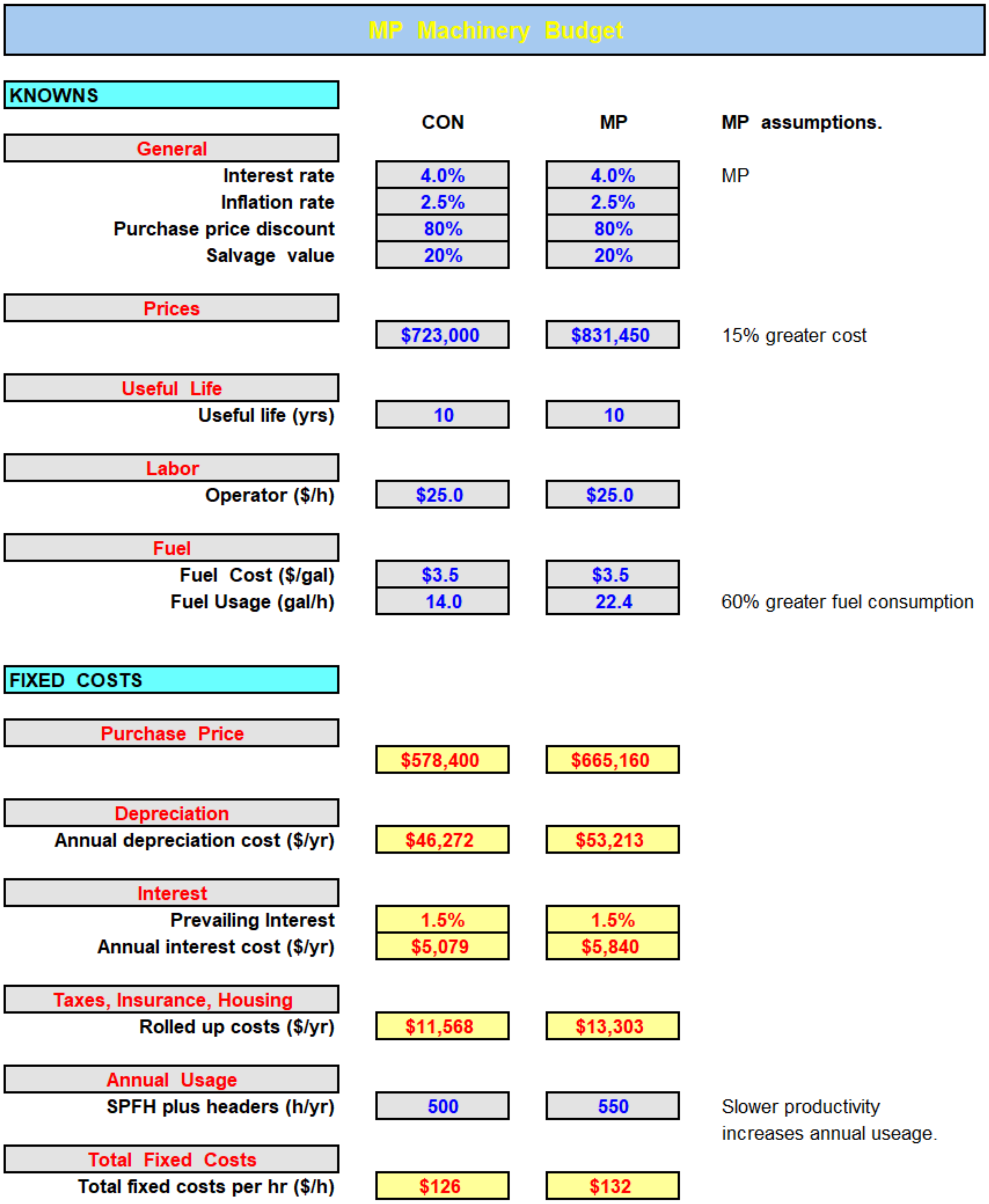
APPENDIX B

The intensive mechanical processing system (MP) requires greater power to harvest (Pintens, 2021), so the analysis was conducted assuming that the harvest fuel requirements increased from 20% to 80%. The MP systems will require changes to the mechanical configuration of harvester, so the cost of the forage harvester was assumed to increase from 10% to 25%. A machinery budget for ownership and operating costs of self-propelled forage harvester (SPFH) using the MP system was used to estimate the cost above the conventional system (CON). This budget followed procedures outlined in ASABE Standard D497.7: Agricultural Machinery Management Data. Based on these assumptions and those shown in the budget (Table B.2), the cost of harvesting alfalfa haylage using the MP system was 1.22 to 1.45 times greater than the cost using the CON system (table B.1).

Table B.1 Increase in cost to harvest alfalfa haylage using SPFH with MP system. Values are multiplier of cost to harvest alfalfa haylage using CON system.

Increase in Harvester Fuel Consumption	Increase in Forage Harvester Price			
	10%	**15%**	**20%**	**25%**
20%	1.22	1.27	1.31	1.35
40%	1.25	1.30	1.34	1.39
60%	1.29	1.33	1.37	1.42
80%	1.32	1.36	1.41	1.45

Table B.2 Machinery budget for ownership and operating costs of self-propelled forage harvester using the MP system to estimate the cost above the conventional system (CON). This scenario was for a MP system with 15% greater retail list price, 60% greater fuel consumption, and 10% slower productivity.



MP Machinery Budget

KNOWNS	**CON**	**MP**	**MP assumptions.**
General			
Interest rate	4.0%	4.0%	MP
Inflation rate	2.5%	2.5%	
Purchase price discount	80%	80%	
Salvage value	20%	20%	
Prices			
	$723,000	$831,450	15% greater cost
Useful Life			
Useful life (yrs)	10	10	
Labor			
Operator ($/h)	$25.0	$25.0	
Fuel			
Fuel Cost ($/gal)	$3.5	$3.5	
Fuel Usage (gal/h)	14.0	22.4	60% greater fuel consumption
FIXED COSTS			
Purchase Price			
	$578,400	$665,160	
Depreciation			
Annual depreciation cost ($/yr)	$46,272	$53,213	
Interest			
Prevailing Interest	1.5%	1.5%	
Annual interest cost ($/yr)	$5,079	$5,840	
Taxes, Insurance, Housing			
Rolled up costs ($/yr)	$11,568	$13,303	
Annual Usage			
SPFH plus headers (h/yr)	500	550	Slower productivity increases annual useage.
Total Fixed Costs			
Total fixed costs per hr ($/h)	$126	$132	

VARIABLE COSTS

Inflation Adjusted Pu Price			
	$925,501	$1,064,326	
Labor			
Operator ($/h)	$25.0	$25.0	
Fuel & Lube			
Fuel ($/h)	$49.0	$78.4	
Oil & Lube ($/h)	$7.4	$11.8	
Repairs Factors			
	RF1	RF2	
RF1	0.030	0.035	Slightly greater R & M costs
RF2	2.00	2.03	
Repair Costs			
Accumulated costs during lifetime	$694,126	$1,175,919	
R & M costs per hr ($/h)	$139	$214	
Total Variable Costs			
Rolled up operating costs ($/h)	$220	$329	

TOTAL COSTS

	CON	MP	
Fixed ($/h)	$126	$132	
Variable ($/h)	$220	$329	
Total ($/h)	$346	$461	
Added cost of ExMP		1.33	Multiply of CON costs.

APPENDIX C

A partial budget was used to estimate the income over feed costs (IOFC) for the CON and MP diets. The diet and the resulting feed efficiency from the lactation study were used as major assumptions. The analysis assumed the herd average would remain the same, but cows fed the MP diet would require less feed due to the improved feed efficiency of the MP diet found in the lactation study. The IOFC was approximately 1.04 times greater for the MP diet than the control diet (table C.1). The IOFC was insensitive to cost of harvesting alfalfa haylage.

Table C.1 Partial budget used to estimate income over feed costs for the MP diet when cost to harvest MP alfalfa haylage varied from 1.22 to 1.45 times than of the CON.

Feed Price ($/ton AF)	Milk Price ($/cwt)	Milk Production (lb./yr)	Haylage in Diet (%)	Cost to Harvest Haylage ($/AF ton)	Feed Effciency (lb./lb.)	Feed Required (tons AF/cow/yr)	Haylage Harvest Cost ($/cow/yr)	Feed Cost ($/cow/yr)	Total Feed Cost ($/cow/yr)	Income Over Feed Cost (IOFC) ($/cow/day)	Additional IOFC with 500 cows
				Conventional Diet							
115	18	25,000	30%	7.0	1.60	17.4	46.9	1,997	2,043	6.73	
				Mechanically Processed Diet							
115	18	25,000	30%	8.5	1.69	16.4	54.1	1,890	1,944	7.00	$49,528
115	18	25,000	30%	8.8	1.69	16.4	55.5	1,890	1,946	7.00	$48,863
115	18	25,000	30%	9.0	1.69	16.4	56.8	1,890	1,947	6.99	$48,197
115	18	25,000	30%	9.2	1.69	16.4	58.1	1,890	1,948	6.99	$47,531
115	18	25,000	30%	9.4	1.69	16.4	59.5	1,890	1,950	6.99	$46,866
115	18	25,000	30%	9.6	1.69	16.4	60.8	1,890	1,951	6.98	$46,200
115	18	25,000	30%	9.8	1.69	16.4	62.1	1,890	1,952	6.98	$45,534
115	18	25,000	30%	10.0	1.69	16.4	63.5	1,890	1,954	6.98	$44,869
115	18	25,000	30%	10.2	1.69	16.4	64.3	1,890	1,955	6.97	$44,425