ALTERING PHYSICAL PROPERTIES OF WILTED ALFALFA BY IMPACT – SHREDDING PROCESSING

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HIGHLIGHTS

- A screenless hammermill utilizing impact and shredding was used to process wilted alfalfa.
- Processing increased specific surface area and ruptured plant cells as quantified by a processing level index.
- Processed material was more compliant than the chopped material resulting in 26% to 56% greater compacted density.
- Processing reduced silage pH and increased fermentation acids compared to the chopped silage.

ABSTRACT. *Intensive mechanical processing of wilted alfalfa could potentially increase ruminant utilization of alfalfa. A novel forage processing mechanism which combines impact and shredding was used to investigate intensive physical disruption of wilted alfalfa. Physical disruption was quantified by a processing level index (PLI) defined as the ratio of treatment leachate conductivity relative to that of an ultimately processed treatment. Utilizing this index, four processing levels defined by the number of passes through the processor were compared to a control treatment of conventionally chopped material. Processing three times through the processing device achieved a PLI of greater than 60%, with the greatest increase in PLI occurring in the first pass through the device. Processing reduced particle-size, but 45% to 56% of the material dry mass was greater than 6 mm at the greatest processing level. Processing severely disrupted the mechanical structure of the stems, making them more compliant resulting in 26% to 56% greater compacted density than the chopped control. Processing reduced silage pH and increased fermentation acids compared to the chopped silage, indicating processing improved silage quality.*

Keywords. *Alfalfa, Density, Haylage, Impact, Particle-size, Shredding.*

Wilted alfalfa intended for storage as haylage requires multiple harvest events in a growing season, is subject to weather-related losses, and requires careful cutting management to avoid over-maturity. Allowing alfalfa to mature longer would reduce the number of cuttings and lead to increased yield, but at the expense of forage nutritive value, specifically an increase in indigestible fiber (Brink et al., 2010). Efforts have been made to enhance alfalfa fiber digestion by mechanical processing, genetic modification, chemical application, and biological treatments (Adesogan et al., 2019). Past work has demonstrated that macerating fresh and unwilted alfalfa ruptured cell walls and increased specific surface area (Kraus et al., 1997; Savoie, 2003). Macerating unwilted alfalfa was shown to increase microbial attachment in the rumen and enhance forage digestibility and animal performance (Hong et al., 1988). *In vitro* and *in situ* studies using unwilted alfalfa have shown that maceration increased the size of the rapidly soluble dry matter (DM) pool, decreased lag time associated with fiber digestion, and increased the extent of fiber digestion (Kraus et al., 1997).

Although macerating alfalfa showed promise, the process was applied to fresh, rather than wilted, crops. While the maceration process was extensively researched, it was never commercialized, primarily because of high losses incurred when the highly processed material was placed back on the stubble for wilting. Intensive processing after wilting and at chopping would not have this issue to overcome, therefore this research focused on intensive processing after the crop had wilted to a DM content appropriate for ensiling.

Previous research has shown that physical disruption of alfalfa by mechanical processing improved digestibility in ruminants but quantifying and reporting processing level was sporadic. A processing level index (PLI) has been suggested as a means to quantify processing level so that comparisons can be made across studies. The PLI was the quotient of ion conductivity of the leachate after water extraction compared to an ultimate treatment of pureeing in a

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blender (Kraus et al., 1999; Buckmaster, 2008; Pintens et al., 2022). Previous research (Kraus et al., 1997; Shinners et al., 2000) has shown that improvement in alfalfa fiber digestion began to plateau at approximately 60% PLI, so this was the target level of physical disruption in this research.

Most previous work on mechanical processing as a means to improve alfalfa digestibility focused on shredding the crop between counterrotating rolls operating at small clearances and differential speeds (Charmley et al., 1997; Shinners et al., 2000; Samarasinghe et al., 2019). More recently processing wilted alfalfa by high-speed impact produced a significantly greater rapidly soluble fraction and faster rates of DM and fiber degradation during *in situ* digestion experiments (Pintens et al., 2022).

Processing wilted alfalfa improved alfalfa digestibility but research was needed to understand how operating variables and crop conditions influenced the physical disruption of wilted alfalfa processed by impact and shredding. Therefore, the project objectives were to: (a) modify a hammermill to process crops through a combination of impact and shredding; (b) quantify the physical and fermentation properties of intensively processed wilted alfalfa; (c) quantify the processor power requirements; and (d) determine the effect on processing level of such variables as DM content and process timing (i.e., at harvest or post ensiling).

MATERIALS AND METHODS

PROCESSING EQUIPMENT DESCRIPTION

Processing through a combination of impact and shredding produced a greater level of processing than by shredding alone (Pintens et al., 2022), so a screenless hammermill was developed to process wilted alfalfa in this fashion (fig. 1). The high-speed hammers created disruption by impact with some additional attrition by shredding as the material is dragged along the roughened surface of the scroll. The experimental impact-shredding processor (ISPr) consisted of a 50 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 peripheral speed of the hammers was 55 or 73 m·s^{-1} depending on the experimental treatment. The typical hammermill screen was replaced with a scroll without openings. Crop material was deposited tangentially into the path of the hammers and was then abraded along the scroll through an arc of 180 degrees before exiting tangentially (fig. 1). The inside surface of the scroll was fabricated of roughened diamond plate (part number 3DRW1, Grainger, Chicago, Ill.). The ISPr rotor was powered by a John Deere (Moline, Ill.) model 6195R tractor through a belt drive that increased rotor speed to a maximum of 2780 rev·min^{-1} when the tractor PTO was operated 1000 rev·min^{-1}. There was no material recirculation observed, so the time to traverse the 0.785 m arc from the input to the exit was less than 0.02 s at hammer tip speed of 55 m·s^{-1}.

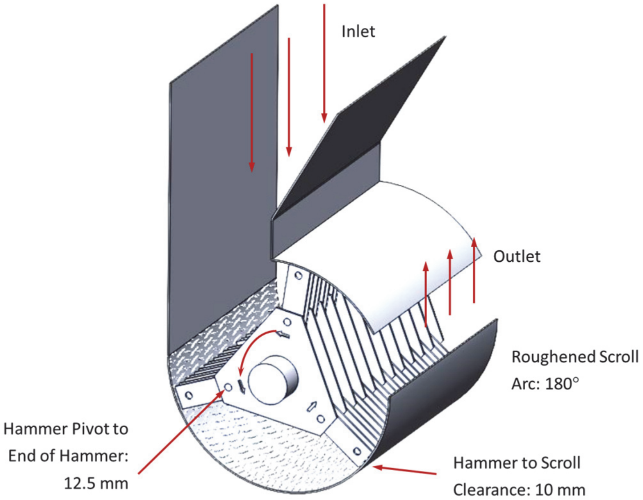

Figure 1. Schematic of impact-shredding processor (ISPr).

EXPERIMENTS CONDUCTED

After field wilting, alfalfa was harvested using a John Deere model 6950 forage harvester set at 35 mm theoretical-length-of-cut (TLOC). The alfalfa was planted in May 2017 and when this research was conducted in 2020 was in the fourth year of production. Alfalfa variety was Croplan HVXRR 4.0. Treatments investigated included a chopped but unprocessed (UP) treatment which was considered the control; and up to four processed treatments consisting of UP material that was subsequently processed one to four times through the ISPr (1X, 2X, 3X, or 4X, respectively). In all experiments there were three replicates per treatment and treatments and replicates were processed in random order. Except when power requirements were measured (described below), the ISPr was fed with a 28 cm wide by 5.5 m long conveyor. Typical mass processed per replicate was approximately 16 kg wet matter (WM).

A total of ten experiments were conducted in 2020 over three cuttings of alfalfa (table 1). Experiments 1 through 3 were conducted to investigate the impact of processing at three levels of crop maturity. This was accomplished by harvesting and processing first cutting wilted alfalfa on three different days (table 1).

Experiments 4 and 5 were performed to investigate the effect of processing either at harvest or after ensiling. At the time of these two experiments, additional UP material was placed into one of three replicate 19 L plastic containers, compacted using the procedure descried below and then sealed. These pilot-scale silos were stored indoors at approximately 20°C for 64 and 63 days for Experiments 4 and 5, respectively. After these ensiling durations, the contents of the three replicate containers per experiment were removed, consolidated, and homogenized by hand mixing. The consolidated material was then separated into 12 subsamples, nine of which were then processed in the ISPr from one to three times (three replicates per treatment) using the procedures described above.

Experiment 6 was conducted to study the effect of processor speed (55 or 73 m·s^{-1}). Processor speed was varied by varying tractor PTO speed. Experiments 7 and 8 were conducted to quantify the specific-energy-requirements (SER)

Table 1. Experiments conducted in 2020 using the impact-shredding processor (ISPr) to process wilted alfalfa.

	Experiment Number	Experiment Date	Approximate Maturity (% bloom)	Avg. DM Content ($g \cdot kg^{-1}$)	Mass-Flow into Processor ($kg \cdot DM \cdot s^{-1}$)	Rotor Tip Speed[a] ($m \cdot s^{-1}$)	No. of Processing Treatments[b]	Experimental Goal
First cutting alfalfa	1	2-Jun	0	348	0.55	55	1X, 2X, 3X	Maturity[c]
	2	7-Jun	5	462	0.82	55	1X, 2X, 3X	Maturity[c]
	3	12-Jun	10	387	0.78	55	1X, 2X, 3X, 4X	Maturity[c]
Second cutting alfalfa	4	8-Jul	25	272	0.93	73	1X, 2X, 3X	Process Timing[d]
	5	9-Jul	35	368	1.10	73	1X, 2X, 3X	Process Timing[d]
	6	13-Jul	60	380	1.03	55, 73	1X, 2X, 3X	Processor Speed[e]
	7	20-Jul	80	410	1.21	73	1X, 2X, 3X, 4X	Process Energy[f]
Third cutting alfalfa	8	29-Jul	0	335	1.64	73	1X, 2X, 3X	Process Energy[f]
	9	31-Jul	5	351	1.19	73	1X, 2X, 3X	Particle Size[g]
	10	6-Aug	20	220 – 410	1.16	73	3X	DM Content[h]

[a] Maximum peripheral velocity of the tip of the hammers in the ISPr.

[b] Number of processing operations in the ISPr which varied from one to four (1X, 2X, 3X, or 4X).

[c] Investigate the impact of processing at three levels of crop maturity.

[d] Investigate the effect of processing either at harvest or after ensiling.

[e] Investigate the effect of processor peripheral velocity.

[f] Quantify the specific-energy-requirements of processing.

[g] Investigate the effect of particle-size on processing level.

[h] Quantify the effect of DM content on processing level.

of processing. Four and three processing operations (1X, 2X, 3X, and 4X – Experiment 7; 1X, 2X, and 3X – Experiment 8) were used. A self-unloading forage wagon was used to collect UP material chopped at 35 mm TLOC. To perform a test, material was deposited from the forage wagon into a silo blower which fed the ISPr. Load cells on the forage wagon were used to measure the mass processed per test. Typical mass processed per test was 200 kg WM and each treatment was replicated three times. During a test, the rate of fuel use was recorded from the tractor's controller area network (CAN) bus with a USB to CAN adapter (ECOM, EControls, San Antonio, Tex.) connected to the tractor's diagnostic CAN terminal. The fuel message (PGN 65203, J1939) was sampled at 10 Hz, decoded, and exported to an Excel spreadsheet by EControls CANCapture Version 3.5 software. Nebraska Tractor Test (NTT Test Report 2105) data for the John Deere 6195R tractor was used to develop a linear model to predict tractor PTO power from recorded CAN fuel rate ($R^2 = 0.999$). Material mass-flow-rate was calculated by dividing mass processed per test by processing time. The specific energy required was calculated by dividing PTO power by mass-flow-rate.

Experiment 9 was performed to investigate if changes in observed physical properties was due to greater exposure of internal plant components or simply due to smaller particle-size caused by processing. Three UP treatments were chopped at 11, 16, or 25 mm TLOC to create different particle-sizes without processing. The 1X, 2X, and 3X treatments were created by processing UP material chopped at 35 mm TLOC. Experiment 10 was conducted to quantify the effect of DM content on processing level. Crop was chopped at 35 mm TLOC four times during a single day to achieve different DM contents and only the 3X treatment was created.

PROPERTIES QUANTIFIED

For all experiments and treatments, two samples per replicate were collected to determine DM content by oven drying at 105°C for 24 h in accordance with ASABE Standard S358.3 (ASABE Standards, 2017). In some experiments, one sample per replicate of approximately 6 L was collected to determine whole-plant geometric-mean particle-size (GMPS) using procedures described in ASABE Standard S424.1 (ASABE Standards, 2017).

For all experiments and treatments, leachate conductivity (LC) was used to quantify the crop processing level (Kraus et al., 1999). This procedure was conducted within a few hours of processing. To determine LC, a microwave oven was first used to determine DM content using procedures described in ASABE Standard S358.3 (ASABE Standards, 2017). The calculated DM was used to determine the wet mass needed to create 5 g DM subsamples, which were then individually placed in 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, N.J.) model 4366 conductivity meter. Two samples per replicate were simultaneously analyzed in this manner. To compare processing across treatments, a normalizing treatment was used. This treatment was similar to that described above, except that the shaking step was replaced by processing the mixture in a model KB64 Vanaheim blender (City of Industry, Calif.) for 1 min at no-load speed of 28,000 rev ·min^{-1}. Four blender replicates were created during each experiment. The hypothesis was that this treatment represented the ultimate mechanical processing level possible and thus the maximum LC. A processing level index (PLI) was defined as the ratio of the treatment LC_{tr} to the blender (i.e., "ultimate") treatment LC_{bl}, expressed as a percent:

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

Compacted density of the treatments was determined by placing approximately 2.7 kg DM of forage per replicate into a plastic tube (25 cm inside diameter, 62 cm height, 30 L volume) and compressing the contents with a hydraulic cylinder, which applied force to a 25 cm diameter platen. A relief valve in the hydraulic circuit was set such that the pressure applied by the platen on the face of the material was 140 kPa. This pressure was chosen because it approximates the tire pressure on many bunker-silo packing tractors. The hydraulic cylinder was extended, compressing the material until the desired hydraulic pressure was reached and the cylinder movement stopped due to relief valve actuation. The hydraulic cylinder was held in this position and the height of the compacted material measured by hand to the nearest 1 cm so the volume and density could be calculated.

In Experiments 5 and 6 (table 1) an additional sample of approximately 230 g DM per replicate were placed in individual vacuum pouches and the air evacuated using a vacuum sealer (Minipak, Friulmed, Monfalcone, Italy). This material was ensiled for approximately 250 days before subsequent lab analysis for pH and fermentation products using wet laboratory techniques performed by Rock River Laboratories (Watertown, Wis.).

STATISTICAL ANALYSIS

Factorial analysis using the Standard Least Squares option in the Fit Model platform of JMP Pro (ver. 15, SAS Institute Inc., Cary, N.C.) was used to conduct the statistical analysis. All experiments, except Experiments 4, 5, and 6 were analyzed using one-way ANOVA's. Because there were two variables explored in Experiments 4 and 5, the effect of treatment and process timing were analyzed using two-way ANOVA's. Because there were two variables explored in Experiments 6, the effect of treatment and rotor speeds were analyzed using a two-way ANOVA. All least square means were compared using the Tukey's test. Significant differences were declared at $p < 0.05$, and tendencies were considered at $0.05 < p < 0.10$.

RESULTS

MATURITY

Processing was observed to shred plant stems into strands of fibers (fig. 2). In Experiments 1 through 3, processing level and compacted density tended to decrease with advancing maturity (table 2). For instance, alfalfa processed (3X) 10 days later (12 June vs. 2 June) at similar DM content (388 vs. 346 $g \cdot kg^{-1}$) had lower PLI (47% vs. 64%) and smaller compacted dry basis density (246 vs. 276 $kg \cdot m^{-3}$). The desired PLI of at least 60% was only attained with alfalfa at bud maturity (i.e., 0% bloom) and three passes through the ISPr.

Figure 2. First cutting alfalfa from Experiment 1. Unprocessed (left) or processed with the experimental processor either twice (middle – 2X treatment) or three times (right – 3X treatment).

Table 2. Processing level index (PLI) and compacted density of first cutting wilted alfalfa harvested on three different dates – Experiments 1 to 3.

Date and Experiment No.	Treatment[a]	Processing Level Index[b] (%)	Compacted Dry Basis Density ($kg \cdot m^{-3}$)
2-Jun[c] Exp. 1	UP	19d	211c
	1X	37c	247b
	2X	48b	264ab
	3X	64a	276a
SEM [d]		1.3	5.5
p-value[d]		< 0.001	< 0.001
7-Jun[c] Exp. 2	UP	20b	227c
	1X	32b	258b
	2X	50a	275ab
	3X	58a	286a
SEM [d]		2.1	6.1
p-value[d]		< 0.001	0.001
12-Jun[c] Exp. 3	UP	22e	201d
	1X	30d	224c
	2X	39c	237bc
	3X	47b	246ab
	4X	57a	255a
SEM [d]		1.3	3.5
p-value[d]		< 0.001	< 0.001

[a] Treatments were unprocessed (UP) and processed through experimental processor one to four times (1X, 2X, 3X, and 4X, respectively). All material was first chopped at TLOC of 35 mm.

[b] Processing level index based on treatment leachate conductivity – see equation 1.

[c] Average DM content and approximate maturity provided in table 1.

[d] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

NUMBER OF PROCESSING OPERATIONS

The first pass through the ISPr tended to have the greatest effect on the crop's physical condition, producing the largest increase in both PLI and compacted density. Averaged across Experiment 1 to 3, processing progressively increased PLI by 13, 13, and 11 percentage points, as processing progressed through the 1X, 2X, and 3X treatments, respectively (table 2). The compacted dry basis density progressively increased by an average of 30, 16, and 11 $kg \cdot m^{-3}$ for the 1X, 2X, and 3X treatments, respectively. This trend was consistent across all experiments where compacted density was measured (fig. 3).

PROCESS TIMING AND SILAGE FERMENTATION

Processing either at harvest or after ensiling (Experiments 4 and 5) produced similar trends, but the PLI was significantly greater for all treatments after ensiling (table 3). Both PLI and compacted density were different between experiments because of differences in DM content (272 vs. 368 $g \cdot kg^{-1}$ for Experiments 4 and 5, respectively). The fermentation process produced both lactic and acetic acid (table 4) and the electrical conductivity of solutions increases as the concentration of these acids increases (Payot and Fick, 1997; Salles et al., 2015). In Experiment 6, processing significantly decreased silage pH and increased production of fermentation acids compared to the control (table 4). There was a trend for comparable results in Experiment 5, but the averages were not statistically significant.

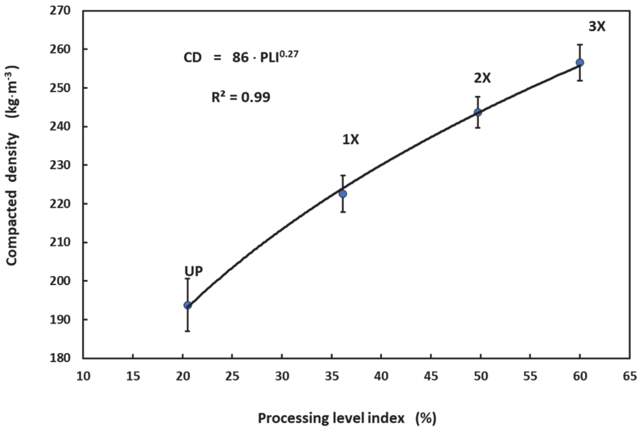

Figure 3. Dry basis compacted density (CD) of the wilted alfalfa vs. processing level index(PLI) for the UP, 1X, 2X, and 3X treatments. Averages from Experiments 1 – 6. Error bars represent the standard error and n = 18.

Table 4. Fermentation properties of four wilted alfalfa treatments harvested on two different dates – Experiments 5 and 6.

				Fermentation products (g·kg^{-1} DM)		
Date and Experiment No.	Treatment[a]	DM (g·kg^{-1})	pH	Lactic Acid	Acetic Acid	Total Acids[b]
9-Jul	UP	358a	4.56a	76a	32a	107a
Exp. 5	1X	369a	4.37a	87a	26a	117a
	2X	370a	4.37a	87a	28a	124a
	3X	371a	4.33a	87a	31a	122a
SEM [c]		4.3	0.058	8.8	2.6	3.9
p-value[c]		0.213	0.061	0.139	0.322	0.068
13-Jul	UP	372a	4.66a	69c	27c	100a
Exp. 6	1X	376a	4.60ab	78b	32b	114b
	2X	371a	4.57b	83ab	33ab	119b
	3X	379a	4.56b	86a	36a	126b
SEM [c]		4.1	0.018	2.5	1.0	2.6
p-value[c]		0.497	0.017	0.006	0.002	0.001

[a] All treatments were chopped at 35 mm TLOC. Treatments were unprocessed (UP) or chopped and then processed through experimental processor one to three times (1X, 2X, and 3X, respectively).

[b] Butyric, propionic, succinic acids and ethanol averaged less than 1 g·kg^{-1} DM and there were no significant differences between treatments.

[c] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

ROTOR PERIPHERAL SPEED

When the speed of the ISPr rotor was increased from 55 to 73 m·s^{-1} in Experiment 6, a greater PLI was realized across all processed treatments (table 5). The PLI was progressively greater by 7, 8, and 13 percentage points at the higher speed when processing was done 1X, 2X, and 3X, respectively. The target PLI of 60% was realized when operating at the greater speed and three processing operations were performed. The dry basis compacted density increased by 6, 13, and 11 kg·m^{-3} at the higher speed when processing was done 1X, 2X, and 3X, respectively.

SPECIFIC ENERGY REQUIREMENTS

In Experiments 7 and 8, the SER ranged from 0.96 to 2.20 kW·h·Mg^{-1} for each pass through the ISPr although the typical range was between 1.0 and 1.3 kW·h·Mg^{-1} (table 6). With each subsequent operation, the additive extent of physical disruption diminished (as quantified by PLI), and the SER tended to decrease. Processing SER was greater when the crop was at a later stage of maturity and at greater DM content (Experiments 7 vs. 8). This was due to the increase in mechanical strength of the crop as it dries (Galedar et al., 2008), as well as the higher levels of fiber and lignin in the mature plant material (Palmonari et al., 2014).

PARTICLE-SIZE

The results from Experiments 7 and 8 show that the PLI of the processed treatments had a strong negative non-linear correlation with GMPS of crop processed with the ISPr (fig. 4). However, the results from Experiment 9 show that the PLI was not significantly different for UP alfalfa that was

Table 3. Processing level index (PLI) and compacted density of second cutting alfalfa when processing was done at harvest or after ensiling – Experiments 4 and 5.

		Harvested 8-Jul (Exp. 4)		Harvested 9-Jul (Exp. 5)	
Processing Treatment[a]	Process Timing[b]	Processing Level Index[c] (%)	Compacted Dry Basis Density (kg·m^{-3})	Processing Level Index[c] (%)	Compacted Dry Basis Density (kg·m^{-3})
UP	At harvest	24f	158c	18g	172c
1X	At harvest	51d	197b	36e	201b
2X	At harvest	70c	241a	53c	231a
3X	At harvest	79b	269a	63b	245a
UP	After ensiling	35e		25f	
1X	After ensiling	67c		48d	
2X	After ensiling	83b		63b	
3X	After ensiling	90a		75a	
SEM [d]		1.0	7.2	0.9	3.8
p-value [d]		< 0.001	< 0.001	< 0.001	< 0.001
Averaged by process timing					
	At harvest	56b		43b	
	After ensiling	69a		53a	
SEM [d]		0.5		0.5	
p-value [d]		< 0.001		< 0.001	

[a] All treatments were chopped at 35 mm TLOC. Treatments were unprocessed (UP) or processed through experimental processor one to three times (1X, 2X, and 3X, respectively). Average DM content and approximate maturity provided in table 1.

[b] Processing took place either at harvest or after anerobic storage and fermentation. Storage duration was 64 and 63 days for Experiments 4 and 5, respectively.

[c] Processing level index based on treatment leachate conductivity – see equation 1.

[d] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

Table 5. Processing level index (PLI) and compacted density of second cutting wilted alfalfa processed at two different processor rotor speeds – Experiment 6.

Processing Treatment[a]	Processor Rotor Tip Speed ($m \cdot s^{-1}$)	Processing Level Index[b] (%)	Compacted Dry Basis Density ($kg \cdot m^{-3}$)
UP		20e	185d
1X	55	30d	213c
2X	55	40c	222bc
3X	55	48b	231ab
1X	73	37c	219bc
2X	73	48b	235ab
3X	73	61a	242a
SEM [c]		0.8	3.4
p-value [c]		< 0.001	< 0.001
Averaged by rotor speed			
	55	39b	222b
	73	47a	232a
SEM [c]		0.5	2.0
p-value [c]		< 0.001	0.005

[a] Treatments were unprocessed (UP) or chopped and then processed through experimental processor one to three times (1X, 2X and 3X, respectively). All treatments were first chopped at 35 mm TLOC. Average DM content and approximate maturity provided in table 1.

[b] Processing level index based on treatment leachate conductivity – see equation 1.

[c] Standard error of the mean. Within each column, lower case markers indicate significant differences at P < 0.05 using Tukey's comparisons.

chopped at three different TLOC (table 7) suggesting that particle-size of unprocessed alfalfa did not influence the PLI. The UP material chopped at 11 mm TLOC had similar GMPS to 1X processed material (16 and 17 mm, respectively) but the PLI was 29 percentage points greater for the latter treatment. Based on these results, it can be concluded that increased PLI from processing was due to rupturing plant cells and exposing more of the internal plant components and that the relationship of GMPS with PLI is a secondary effect.

DM CONTENT

As the crop DM content increased in Experiment 10, the PLI of the processed material significantly decreased (fig. 5). As the crop dries the cells become less turgid (Loper, 1972) and the stem gains mechanical strength (Galedar et al., 2008). These physical changes made it more difficult to achieve a given level of processing. Similarly, Shinners et al. (2000) reported that PLI decreased as DM content increased for alfalfa processed through a forage harvester with conventional shredding crop processing rolls.

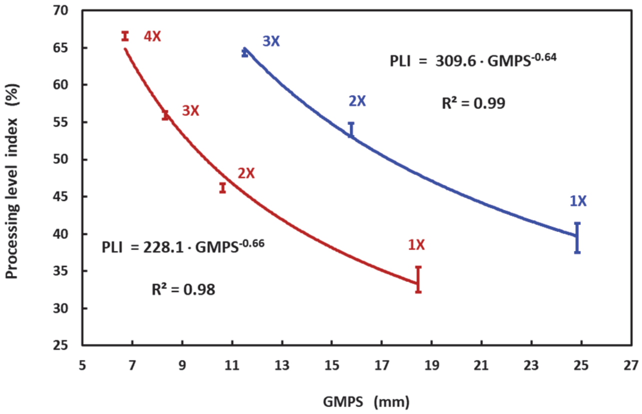

Figure 4. Processing level index (PLI) for wilted alfalfa versus geometric-mean-particle-size (GMPS) for Experiments 7 (red) and 8 (blue). The number of processing operations are identified as 1X, 2X, 3X, and 4X signifying the number of passes through the impact-shredding processor. Error bars represent SEM and n = 3.

DISCUSSION

Intensive forage processing as investigated here disrupted plant tissues and rupture cell walls as quantified by the PLI. Processing in this manner produced favorable rumen digestion response (Pintens et al., 2022). In this research, these physical alterations also produced positive outcomes regarding compacted density and fermentation characteristics. Of concerns are the effect of intensive processing on GMPS, the number of operations required to achieve the desired PLI, and the specific energy requirements.

Intensive processing of forages increases the crops specific surface area which has shown to increase the rate and extent of forage digestion. For instance, *in vivo* digestibility of wilted grass-clover silages tended to be greater for

Table 6. Specific energy (SER) for processing, processing level index (PLI), and particle-size (GMPS) of second or third cutting wilted alfalfa – Experiments 7 and 8.

Date and Experiment No.	Treatment[a]	Processing Level Index[b] (%)	Mass-Flow-Rate[c] ($Mg \cdot h^{-1}$)	Specific Energy[c] ($kW \cdot h \cdot Mg^{-1}$)	Geometric Mean Particle-Size (mm)	Fraction of Mass greater than 6 mm (%)
20-Jul Exp. 7	UP	19e			60a	87a
	1X	34d	10.2a	2.20a	19b	69b
	2X	46c	10.2a	1.25b	11b	57c
	3X	57b	10.0a	1.17b	8b	51d
	4X	67a	12.1a	1.19b	7b	45e
SEM [d]		0.9	1.75	0.069	3.8	1.2
p-value [d]		< 0.001	0.808	< 0.001	< 0.001	< 0.001
29-Jul Exp. 8	UP	22d			55a	86a
	1X	39c	16.6a	1.27a	25b	73b
	2X	54b	18.7a	1.03b	16bc	65c
	3X	64a	17.9a	0.96b	12c	60d
SEM [d]		0.9	1.27	0.059	2.7	0.6
p-value [d]		< 0.001	0.528	0.012	< 0.001	< 0.001

[a] Treatments were unprocessed (UP) and processed through experimental processor one to four times (1X, 2X, 3X, and 4X, respectively). All material was first chopped at TLOC of 35 mm. Average DM content and approximate maturity provided in table 1.

[b] Processing level index based on treatment leachate conductivity – see equation 1.

[c] Mass-flow-rate and specific energy are on a wet basis.

[d] Standard error of the mean. Within each column, lower case markers indicate significant differences at p < 0.05 using Tukey's comparisons.

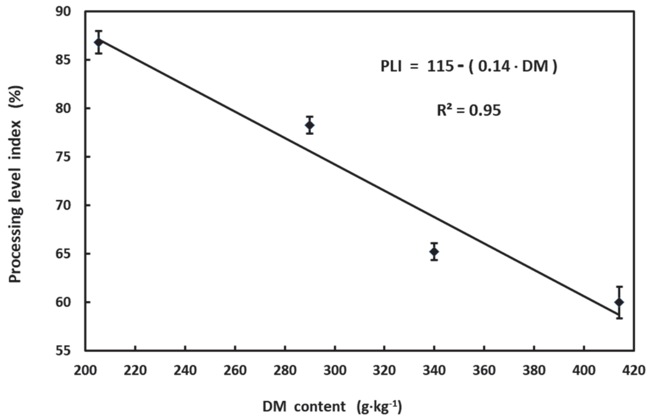

Figure 5. Processing level index (PLI) for alfalfa wilted to different dry matter (DM) contents and processed using the 3X treatment – Experiment 10. Error bars represent SEM and n = 4.

shredded material compared with untreated silage (Weisbjerg et al., 2018). A challenge in assessing the potential for processed wilted forages to improve rumen animal performance is that quantification of processing level is often lacking. Pintens et al. (2022) found that processing wilted alfalfa to PLI levels greater than 60% resulted in increased rate of DM and fiber degradation of alfalfa when evaluated in situ. Additional research should be considered to evaluate the effect of impact-shredding processing on ruminant fiber digestibility and dairy lactation performance. Quantifying processing level, for instance with the PLI metric, should be considered a necessity in these future studies.

Processing made the material more compliant by shredding and fiberizing the stems (fig. 2) so compacted density was greater than chopped material (fig. 3). When the desired PLI of greater than 60% was attained, the average compacted density of processed alfalfa was 26% to 56% greater than the chopped material. Samarasinghe et al. (2019) reported a similar increase in density for shredded low DM alfalfa ensiled in laboratory-scale silos. Wrapped bale density was 25% to 36% greater for shredded grass-clover bales compared control bales (Hansen et al., 2021). Further research is needed to determine if processed forages will result in greater density in a bag or bunk silo using conventional compaction means. Silage density and porosity affect the ingress of oxygen and subsequent heating at the silo face during feed-out (Wilkinson and Davies, 2013). Additional research should be conducted to determine if the greater density with the processed material improves stability during feed out.

Table 7. Processing level index (PLI) and particle-size (GMPS) of third cutting wilted alfalfa using various theoretical-length-of-cut (TLOC) for the unprocessed (UP) treatment – Experiment 9.

Treatment[a]	Theoretical-Length-of-Cut[b] (mm)	Processing Level Index[c] (%)	Geometric Mean Particle-Size (mm)	Fraction of Mass > 6 mm (%)
UP	11	13d	16bc	74bc
UP	16	15d	20b	79b
UP	25	14d	33a	86a
1X	35	42c	17bc	70c
2X	35	58b	12cd	62d
3X	35	67a	9d	56e
SEM [d]		0.8	1.3	1.1
p-value [d]		< 0.001	< 0.001	< 0.001

[a] Treatments were unprocessed (UP) chopped at three different TLOC and processed through experimental processor one to three times (1X, 2X, and 3X, respectively). Average DM content and approximate maturity provided in table 1.

[b] Theoretical-length-of-cut (TLOC) on the forage harvester.

[c] Processing level index based on treatment leachate conductivity – see equation 1.

[d] Standard error of the mean. Within each column, lower case markers indicate significant differences at P < 0·05 using Tukey's comparisons.

Shredding and fiberizing the crop before ensiling improved fermentation properties by making more internal plant substrates accessible for fermentation. Comparable results were found when low DM alfalfa was processed by maceration (Muck et al., 1989; Charmley et al., 1997; Samarasinghe et al., 2019). Silage concentrations of lactic and acetic acids were greater, and pH lower, for shredded grass-clover silages, which indicated silage quality improved from shredding (Hansen et al., 2021).

Processing wilted crop with the screenless hammermill reduced particle size. Ruminants require forage fiber in proper physical form to maintain rumen function (NRC, 2001). Impaired rumen fermentation and function can result from rations lacking in physical structure. A strict definition of adequate alfalfa particle length is not available, but it is recommended that 45% to 75% of alfalfa haylage particles reside on or above an 8 mm screen (Heinrichs, 2013). When the desired PLI of greater than 60% was attained, average GMPS was 7 to 14 mm and average fraction greater than 6 mm was 45% to 56%. Although the physical form of the shredded and fiberized material is quite different from conventional chopped alfalfa (fig. 2), the processed alfalfa met the minimum physical size recommendations.

The experimental ISPr used in this research was able to achieve the goal of 60% PLI, however it took multiple processing operations to achieve this goal. Methods to achieve the desired processing level in a single operation should be investigated. Greater rotor speed increased PLI (table 5) so this variable should be explored as a means to achieve this goal. This approach will require greater energy, so increasing the harvester TLOC should be considered as a means to partially offset the added energy expenditures of processing. Savoie et al. (1989) reported at 22% reduction in chopping energy when TLOC was increased from 6 to 38 mm. Shinners et al. (2000) reported a similar reduction when TLOC was increased from 9.5 to 19 mm with a difference of 0.49 $kW \cdot h \cdot Mg^{-1}$.

Processing wilted alfalfa with conventional shredding crop processing rolls on a forage harvester increased SER by 0.51 $kW \cdot h \cdot Mg^{-1}$ (Roberge et al., 1998). Processing level was not quantified in that research. Shinners et al. (2000) reported SER for processing wilted alfalfa using a single pass through conventional shredding crop processing rolls was 0.93 to 2.38 $kW \cdot h \cdot Mg^{-1}$ and the achieved PLI was less than 50%. For each pass through the ISPr, processing wilted alfalfa required between 1.0 and 1.3 $kW \cdot h \cdot Mg^{-1}$ (table 6). Simply summing the SER across all three passes is not appropriate. The development of an ISPr that achieves the desired processing level in a single-pass will enable a better understanding of the SER of processing by impact and shredding.

Processing could be considered either at harvest or at removal from storage and this was investigated here (table 3). Processing at harvest would provide benefits from greater compacted density (tables 3 and 4) and improved fermentation (table 4). However, processing is energy intensive (table 6) and could reduce harvester productivity. Processing after storage produced greater PLI (table 3) which could result in improved animal performance, but the above benefits from processing at harvest would not be realized. Additional research is needed to determine if processing at harvest or at removal from storage would provide the greatest benefit to the dairy production system.

CONCLUSIONS

Intensive mechanical processing with a screenless hammermill was an effective method to cause physical disruption of wilted alfalfa and subsequently increased the PLI. The physical disruption was the result of both impact and shredding. While processing decreased particle size, an appropriate fraction was greater than 6 mm length. Greater PLI was achieved at lower DM contents. The processed material was more compliant and compacted to greater densities than chopped material. Fermentation properties were improved by processing. Although the processing took significant energy and resulted in an additional step in the harvest process, it showed the ability to produce unique physical properties that could improve ruminant animal utilization. Additional research should be considered that investigates methods to achieve the desired processing level in a single operation, with the minimum energy expenditures. A feeding trial should be considered to understand the implications of feeding this material to lactating dairy cattle.

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