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ORIGINAL ARTICLE

Intensive mechanical processing of forage crops to improve fibre digestion

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Abstract

Two intensive forage processing mechanisms, utilising either shredding or impact processing, were used to investigate physical disruption of wilted alfalfa and whole-plant corn as a potential means to improve fibre digestion. 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. The goal was to achieve a PLI of at least 60%. Impact processing created more physical disruption than shredding, and the former method was able to achieve the desired PLI goal. Although impact processing significantly reduced particle size of both wilted alfalfa and whole-plant corn, more than 40% of alfalfa particles were longer than 6.3 mm when the PLI of greater than 60% was achieved. The mean particle-size of the kernel fraction of processed whole-plant corn was less than 1 mm after processing with the impact processor. Impact processing of wilted alfalfa significantly increased the rapidly soluble fraction and increased the rate of degradation of DM and potentially digestible fibre (pdNDF) during an in situ digestion experiment. Intensive mechanical processing has the potential to improve ruminant animal utilisation of forage crops through improved fibre digestion.

KEYWORDS
alfalfa, fibre digestion, processing, shredding

1 | INTRODUCTION

Fibre is an essential component of diets for ruminant cattle. In high producing dairy cows, as much as a quarter of the energy for milk production comes from digested fibre (Combs, 2014). Because fibre is the slowest digesting fraction of the dairy ruminant diet, both the amount consumed and its digestibility can have a significant impact on overall feed efficiency (Adesogan et al., 2019). Technologies for improving forage crop utilisation through greater fibre digestion include physical and mechanical processing; genetic modification; chemical application and biological treatments (Adesogan et al., 2019).

The most common means of mechanical forage processing is size reduction by chopping with a forage harvester. However, chopping has little impact on digestibility of dietary NDF (Ferraretto & Shaver, 2012). Another common processing method is by shredding whole-plant corn (WPC) with a kernel processor. Although the kernel processor does slightly alter the physical properties of the non-grain fraction of WPC, research results are inconclusive as to whether NDF digestion is improved by this processing technique (Adesogan et al., 2019).

An intensive mechanical forage processing system known as maceration has been investigated (Bacon & Shinners, 2003). At the time of cutting, fresh herbage was subjected to an intensive shredding process that increased the specific surface area and ruptured plant cells. In vitro and in situ studies using alfalfa showed that maceration increased the size of the rapidly soluble DM pool and improved NDF digestion (Kraus et al., 1997). Dairy cattle fed macerated alfalfa showed increased milk production (Broderick et al., 1999; Mertens et al., 1990; Mertens & Koegel, 1996). Although commercialisation of forage maceration was pursued (Haldeman, Kraus, & Shinners, 1999; Schmittbetz & Liebers, 1991), these efforts were abandoned because the physical losses of macerated material placed back on the stubble for wilting were too great. Cutting and wilting as conventionally practiced and then applying intensive mechanical processing at chopping, rather than at cutting, is an alternative approach that could achieve the process benefits of maceration without incurring high field losses.

Research concerning fibre digestibility of forages mechanically processed after field wilting is limited. Weisbjerg et al. (2018) reported that in vivo digestibility of aNDF tended to be greater for shredded compared with untreated silage. A challenge in assessing the efficacy of improving fibre digestibility of processed wilted forages is that quantification of processing level is often lacking. Kraus et al. (1999) suggested a processing level index (PLI) based on the conductivity of a leachate for quantifying the extent of physical disruption caused by various processing treatments. Across several different alfalfa maturities, the extent of DM disappearance of macerated fresh alfalfa plateaued after 6 h when the PLI was between 60% and 70%. Achieving the same level of PLI is more difficult when processing occurs after wilting, rather than at cutting, because the plant cells become less turgid, and the plant gains mechanical strength as it dries. Processing wilted alfalfa with a single pair of shredding rolls resulted in some DM and NDF digestion benefits (Shinners et al., 2000). However, milk yield did not increase, most likely because the PLI of the processed treatment was only 41%. The goal of this research was to investigate intensive mechanical processing technologies that can achieve a PLI of at least 60% when processing wilted alfalfa or whole-plant corn.

The specific objectives of this research were: (a) to use two different mechanical processing technologies to alter forage physical properties and to quantify these properties; (b) to determine if a PLI of at least 60% can be achieved when processing wilted alfalfa with these devices; (c) to conduct an in situ digestion experiment to quantify alfalfa DM and fibre degradation after intensive processing and (d) to use the results to suggest which processing technology warrants further research.

2 | MATERIAL AND METHODS

2.1 | Experimental processors

Experiments were conducted in 2019 using two experimental processors. One employed shredding, while the other utilised impact, as the primary means to physically disrupt the plant structure. The shredding processor (SPr) was similar to that described in Shinners et al. (1988). It used a main cylinder (40 cm diameter), a feed roller and six planetary rolls (10 cm diameter) operating at differential peripheral speed to the drum (Figure 1). Clearance between the drum and rolls was nominally 1 mm. The peripheral speeds of the drum and shredding roll were 28.1 and 10.2 $m{\cdot}s^{-1}$, respectively, so the peripheral speed ratio was 2.74:1. The drum and rolls had a knurled surface to facilitate feeding and shredding. The knurl tooth pitch was 3.2 mm, tooth depth 1.6 mm, with a 45° angular tooth profile. The impact processor (IPr) consisted of two counter-rotating hammer rotors with four hammers per rotor (Figure 2). The hammers were 12 mm thick, traced a tip radius of 175 mm and operated at a peripheral speed of 63 $m{\cdot}s^{-1}$. The vertical distance between the hammer rotors was 180 mm. The clearance between the tip of the hammers and the housing was 12 mm.

2.2 | Processing experiments

Two experiments were conducted using wilted alfalfa. It was hypothesised that processing would have greater impact on the alfalfa stem fraction compared with the leaves, so the first experiment was conducted using only alfalfa stems. An experimental leaf stripper (similar to Shinners et al., 2007) was used to strip leaves from standing

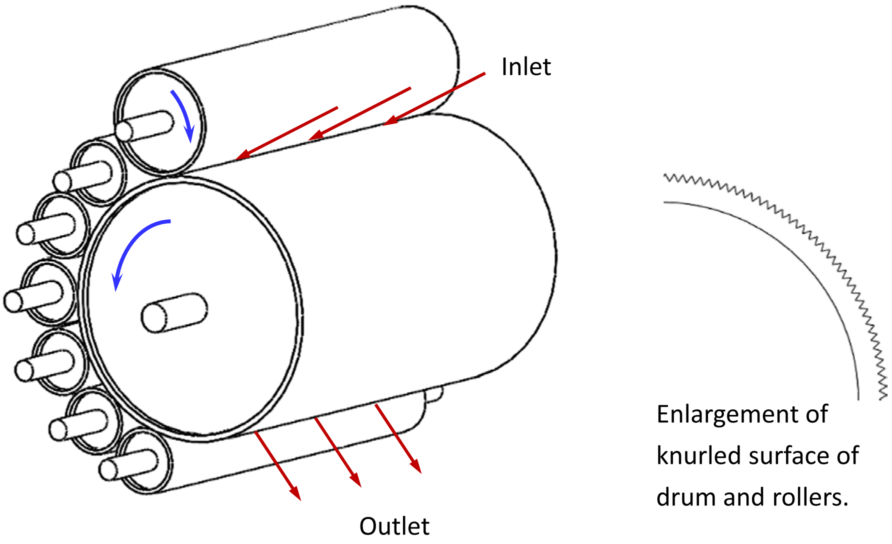

FIGURE 1 Schematic of drum and roll shredding processor (SPr). All the rollers rotated clockwise and peripheral speed differential between the drum and rollers was 2:74:1

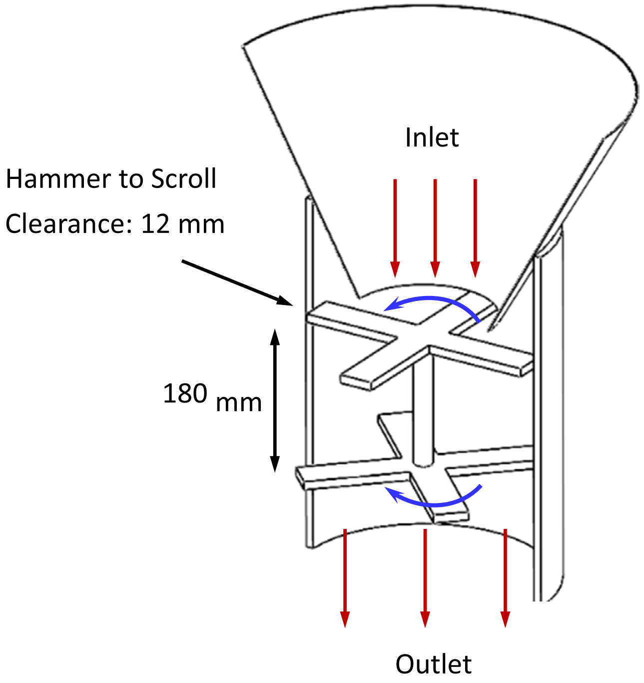

FIGURE 2 Schematic of impact processor (IPr). Peripheral speed of hammers was 63 m·s^{-1}

second cutting alfalfa (~80% bloom). Immediately after stripping, the standing stems were cut, windrowed and allowed to wilt before they were hand collected and transported to the laboratory for processing. Five treatments, with three replicates per treatment, were evaluated: (a) chopped (CHP) with lab scale forage chopper (13 mm theoretical-length-of-cut [TLOC]), (b) processed once through the SPr (SPr-1X), (c) processed thrice through the SPr (SPr-3X), (d) processed once in the IPr (IPr-1X) and (e) processed twice in the IPr (IPr-2X). It was felt that after processing, the particle-length of the two SPr treatments was still too long to facilitate packing in 8 L pilot-scale silos (described below), so these two treatments were chopped after processing using the same lab scale chopper described above (13 mm TLOC). Material processed in the IPr was not chopped. A second experiment was conducted using whole-plant third cutting alfalfa (~10% bloom). Other than the leaf stripping operation, this experiment was designed identically to the first.

A sub-sample from each replicate was collected to determine DM content by oven drying at 105°C for 24 h in accordance with ASABE Standard S358.3 (2017). An additional sub-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 (2017). Material at harvested moisture was separated using a cascade of screens (19.0, 12.7, 6.3 and 4.0 mm) oscillated in horizontal plane for 2 min (Finner et al., 1978). The fraction of the total mass residing on or above the 6.3 mm screen was also calculated.

Leachate conductivity (LC) was used to quantify the level of crop processing (Kraus et al., 1999). Electrical conductivity of a solution is proportional to its ion concentration. 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. A microwave oven was first used to determine the average DM content of three random sub-samples using procedures described in ASABE Standard S358.3 (2017). The calculated DM was used to calculate the wet mass needed to create 5 g dry mass sub-samples. Each sub-sample was 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 model 4366 conductivity meter. Two sub-samples per replicate were processed in this manner. To compare processing across treatments, a normalising 'ultimately processed' treatment was produced. This treatment was similar to that described above except that the shaking step was replaced by processing the mixture in a Vanaheim model KB64 blender for 1 min at 28,000 rpm no-load speed. The hypothesis was that this treatment represented the maximum or ultimate mechanical processing level possible and thus the maximum LC. Using this treatment, a processing level index (PLI) was defined as the ratio of the treatment LC_{tr} to the blender LC_{bl}, expressed as a percent:

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

To preserve material for an in situ digestion experiment, material was conserved in 8 L pilot-scale silos. Processed material was placed in a pilot-scale silo by hand and then compacted with a hydraulic press. After an initial compaction, the container was refilled and recompacted. This process was repeated until no more material could be placed in the container. The container and its contents were then weighed to the nearest 0.1 kg, sealed with a locking lid with rubber gasket and stored indoors until used for the in situ digestion experiment. Compacted dry mass and container volume were used to calculate silo pack density.

A single experiment was conducted using WPC that was harvested using a Case IH (Racine, WI, USA) model FX300 forage harvester set to operate at 19 mm TLOC and then processed through the harvester's on-board kernel processor. This material was considered the control treatment (CHP). The processor treatments were SPr-1X, SPr-2X and IPr-1X, IPr-2X. The DM content, GMPS, LC and PLI were determined using similar procedures as described above.

An additional two sub-samples per replicate of WPC were collected to quantify kernel particle-size. These samples were oven dried for 24 h at 55°C and the kernel fraction was separated from the stover following a water separation procedure described in Savoie et al. (2004). After separation, the kernels were oven dried for 24 h at 55°C and then fractionated by size using a cascade of screens in a Ro-Tap screener (W.S. Tyler; Mentor, OH, USA). The screener was configured with five screens (6.3, 4.0, 2.8, 2.0, and 1.2 mm) and a bottom pan. After operating the screener for 2 min, the contents of each screen and the pan were weighed to the nearest 0.001 g and the kernel GMPS calculated using procedures found in ASABE

Standard S319.4 (2017). The fraction of the total mass residing on screens below the 6.3 mm screen was also calculated.

Statistical analysis of these experiments was completed using the Standard Least Squares option in the Fit Model platform of JMP Pro (ver. 15, SAS Institute Inc.). Experiments were analysed using one-way ANOVA using the model:

$$Y_{ij} = \mu + T_i + E_{ij} \tag{2}$$

where μ is the overall mean, T_i is the processing treatment and E_{ij} is the residual error. All least square means were compared using Adjusted Tukey's test. Significant differences were declared at $p \le 0.05$, and tendencies were considered at $0.05 < p \le 0.10$.

2.3 | In situ digestion experiment

Rumen degradation characteristics of two ensiled treatments (CHP and IPr-2X) of both alfalfa stems and whole-plant alfalfa were determined using the in situ technique. The CHP treatment served as the control and the IPr-2X treatment was chosen because it had the greatest PLI. Pilot-scale silos (described above) of these treatments were opened after 118 days in storage and the contents were homogenised. Three sub-samples per treatment were then randomly collected from the homogenised mass, oven dried at 55°C for 72 h in a forced air drier and then ground in a Wiley mill (1 mm screen). These samples were then analysed for CP, aNDF, ADF and ash using wet chemistry techniques by Rock River Laboratories.

Because the goal of this experiment was to determine the ruminal DM and NDF disappearance based on physical differences between treatments, samples were not ground but rather were placed in the rumen bags in their 'as-fed' physical form. This procedure is similar to that successfully used by Shinners et al. (2000). Approximately, 25 g of DM were placed in 250 × 350 mm polyester 'macro-bags' (52 μm pore size) and sealed. These macro-bags were then placed in a mesh laundry bag. Two laundry bags, each containing eight macro-bags of one treatment, were placed in the rumen at 8:00 am after the morning feeding. The rumen incubations were performed according to an 'all in/gradual out' schedule. Incubations were carried out for 3, 6, 12, 24, 36, 48, 120 and 240 h. After 48 h, another two mesh laundry bags were placed in the rumen to begin the second replicate of the experiment. Two fistulated multiparous Holstein dairy cows in late lactation (315 +/- 50 days in milk) were used. The experiment consisted of four replicates per treatment—two cows by two dates. The ration consisted of 3.5% straw, 9.9% alfalfa hay, 6.3% ground corn grain, 34.8% whole-plant corn silage and 45.5% alfalfa haylage on a DM basis. This experiment was conducted using a protocol approved by the Institutional Animal Care and Use Committee at the University of Wisconsin.

At the appropriate time, macro-bags were removed from the rumen and placed in a container of cold water to stop microbial activity. The bags were then rinsed twice consecutively using a conventional clothes washer. The rinse cycle consisted of 5 min fill (68 L), agitation for 2 min (130 cycles) and a 3 min spin cycle. The washed samples were then dried at 55°C for 48 h in a forced air drier, the dry mass was then measured and DM loss calculated. To determine the rapidly soluble fraction, two macro-bags per treatment at each of the two initial insertion times containing approximately 25 g DM of 'as-fed' material was soaked in lukewarm water for 30 min, and then rinsed, oven dried and weighed as described above. After oven drying, the contents of each macro-bag were ground in a Wiley mill (1 mm screen) to facilitate determination of NDF content, which was performed using wet chemistry techniques by Rock River Laboratories.

The in situ disappearance of DM or NDF (Y_{disp}) with time was modelled as a negative exponential curve with a lag phase (Ørskov & McDonald, 1979):

$$Y_{disp} = A + B \cdot \left(1 - e^{-k_{d1} \cdot (t-L)}\right) \tag{3}$$

where A is the rapidly soluble fraction at 0 h after the rinsing procedure (%); B is the slowly degradable fraction (%); k_{d1} is the degradation rate constant (h^{-1}) of fraction B; t is time (h) and L is the degradation lag time (h). The undegradable fraction (C) was calculated as 100–A–B. The model constants for Equation 3 were determined iteratively using NLIN function in SAS (ver. 15, SAS Institute Inc.).

Effective degradability of DM and NDF (Y_{degrad}) was calculated using (Ørskov & McDonald, 1979):

$$Y_{degrad} = A + B \cdot \left(\frac{k_{d1}}{(k_{d1} + k_p)}\right) \tag{4}$$

where A, B and k_{d1} are the same as defined in Equation 3, and k_p is the rate of passage assumed here as 0.06 h^{-1}.

Forage NDF consists of two components, a potentially digestible component (pdNDF) and an indigestible component (iNDF) (Combs, 2014). The pdNDF as a fraction of NDF was calculated using (Bender et al., 2016):

$$pdNDF\left(\frac{g}{g}\right) = \frac{(NDF_{0h} - NDF_{residue})}{NDF_{0h}} \tag{5}$$

where NDF_{0h} is the initial mass of NDF, and $NDF_{residue}$ is the mass of NDF remaining at 240 h. The fraction of pdNDF remaining at each time point (t), expressed as a percent, was calculated from:

$$pdNDF_{remaining}(\%) = \left(1 - \left(\frac{(pdNDF_{0h} - pdNDF_t)}{pdNDF_{0h}}\right)\right) \cdot 100 \tag{6}$$

where $pdNDF_t$ is the mass of pdNDF remaining at time point t. The rate of pdNDF degradation was determined as the slope of the natural logarithm-transformed fractions of pdNDF versus time (Bender et al., 2016):

$$\ln(pdNDF_{remaining}) = I + (t \cdot \le (-k_{d2})) \tag{7}$$

where I is the intercept, and k_{d2} is the slope which represents the fractional rate of disappearance of pdNDF. Based on suggestions made by Bender et al. (2016), samples that had not reached 5% of pdNDF degradation were not included in the determination of the rate constant k_{d2}.

3 | RESULTS

3.1 | Processing experiments

Compared with the control (CHP), processing significantly increased the PLI when either processor was used on wilted alfalfa (Table 1). Processing improved PLI of both the stems and the whole-plant. The IPr-2X produced significantly greater PLI than the SPr, even when material was processed three times with the latter processor. A single pass through the IPr produced a similar PLI to three passes through the SPr for both stems and the whole-plant. Only the IPr was able to achieve the desired goal of a PLI greater than 60%, but it took two passes through the processor to achieve this processing level. When third cutting whole-plant material was processed, a separate SPr-1X treatment was processed before any wilting. The PLI was 49.9% and 38.5% when processing took place before and after wilting, respectively (238 $g\cdot kg^{-1}$ and 353 $g\cdot kg^{-1}$ DM content, respectively).

It was observed that the material processed by the IPr had more individual fibre strands than that processed in the SPr, even when the latter was processed three times (Figure 3). Some stems processed with the SPr were not longitudinally sheared but rather only had the epidermis removed. It was rare to find stems that had not been fibreised when processed with the IPr. It was observed that the highly fibreised material processed with the IPr was more compliant than the control or material processed with the SPr, which resulted in significantly greater compacted density in the pilot-scale silos with the IPr treatment (Table 1). The compacted density of the IPr-2X whole-plant alfalfa treatment was 75% greater than the control CHP treatment.

Compared with the control (CHP), processing twice in the IPr significantly reduced the GMPS of both the stems and the whole-plant (Table 1). The IPr caused greater reduction in particle-size than the SPr even though material was chopped with the latter processor and was not chopped in the former. Processing by shredding with the SPr left more of the stem fraction intact than processing by impact (Figure 3), which contributed to the greater GMPS with this treatment.

TABLE 1 Physical properties of wilted alfalfa processed using the shredding (SPr) or impact (IPr) processors

Treatment[4]	DM content (g·kg^{-1})	Processing level index[1] (%)	Pliot-scale silo compacted dry basis density (kg·m^{-3})	Geometric-mean particle-size[2] (mm)	Fraction of mass greater than 6.3 mm[3] (%)
Second cutting aflafa stems					
CHP	340a	12.6d	170d	25a	72a
SPr–1X	312c	33.6c	204c	27a	71a
SPr–3X	322bc	51.1b	243b	22ab	68a
IPr–1X	330ab	54.2b	264a	17ab	54b
IPr–2X	325b	69.6a	271a	9b	41c
SEM[5]	2.7	0.93	3.3	2.4	2.2
p-values	<0.001	<0.001	<0.001	0.016	0.001
Third cutting whole-plant aflafa					
SPr–1X	238e	49.9b			
CHP	324d	12.4d	184d	22ab	69a
SPr–1X	353bc	38.5c	205c	24a	70a
SPr–3X	373ab	55.4b	308a	13ab	58b
IPr–1X	350c	55.6b	267b	13ab	58b
IPr–2X	380a	65.6a	322a	10b	53b
SEM[5]	4.7	1.91	3.2	2.4	1.3
p-values	<0.001	<0.001	<0.001	0.031	0.001

[1] Processing level index based on leachate conductivity of treatment – see Equation no. 1.

[2] Geometric-mean particle-size based on screening following ASABE Standard S424.1.

[3] Fraction of mass residing on top three screens (i.e., fraction over 6.3 mm) of ASABE S424.1 screener.

[4] Treatments are chopped (CHP); processed using the shredding processor either one or three times (SPr-1X and SPr-3X) and processed using the impact processor either one or two times (IPr-1X and IPr-2X). *n* = 3 for each treatment.

[5] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < .05$ using Tukey's comparisons.

FIGURE 3 From left to right: chopped control (CHP); processed three times with the shredding processor (SPr-3X) and processed twice with the impact processor (IPr-2X)

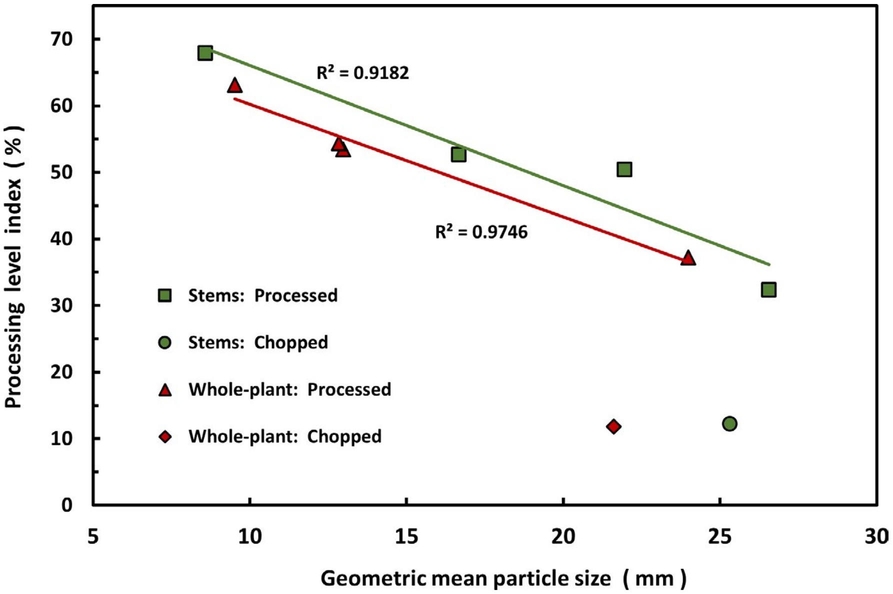

FIGURE 4 Geometric mean particle size (GMPS) versus processing level index (PLI) for wilted alfalfa stems or wilted whole-plant alfalfa. Standard error of the PLI means were less 2% points for all data and *n* = 4

The PLI was linearly correlated with GMPS for the processed treatments (Figure 4) with greater PLI as GMPS declined. Although the GMPS was similar for the CHP and SPr-1X treatments (Table 1), the PLI was statistically greater for the latter treatment. Therefore, increased PLI from processing was likely due to rupturing plant cells and exposing more of the internal plant components rather than simply due to reduced particle-size.

Compared with the control, processing significantly increased the PLI when either processor was used on WPC (Table 2). Differences in the PLI between processed treatments were less with WPC than with alfalfa haylage. Processing with IPr resulted in significantly greater compacted density compared with the control treatment. The compacted density of the IPr-2X treatment was 19% greater than the control CHP treatment, a much smaller difference than found with wilted alfalfa. Kernel fraction particle-size of all the SPr and IPr processed treatments was significantly less than the CHP control treatment and there were no statistical differences between the processed treatments. Greater than 90% of the kernel particles were less than 6.3 mm with all processed treatments. Compared with the CHP treatment, the whole-plant GMPS was less for both IPr treatments, which was likely due to reduction in size of both the stover and grain fractions.

3.2 | In situ digestion experiments

There were no significant differences in composition between the CHP and the IPr-2X stem or whole-plant treatments (Table 3). Nutrient composition of the whole-plant alfalfa was typical of third cutting alfalfa typically used as part of dairy rations in the Midwest of the United States. Composition of the stem fraction was similar to that reported by Adapa et al. (2003).

Processing twice through the IPr resulted in a greater rapidly soluble DM fraction (A) with whole-plant alfalfa (significant) and alfalfa stems (trend) (Table 4; Figure 5). The effective ruminal DM degradability calculated using Equation 4 was significantly greater for both processed alfalfa stems and whole-plant alfalfa (Table 4). There were no significant differences in effective ruminal NDF degradability calculated using Equation 4, although there was a trend for greater NDF degradability with the IPr-2X treatment with whole-plant alfalfa (Table 4). The rate of pdNDF degradation of both wilted whole-plant alfalfa and alfalfa stems was numerically greater for material processed with IPr-2X compared with the control (Table 5; Figure 6). The rate constants (k_d, Equation 7) ranged from 2.9% to 3.7%, which were less than the typical values for alfalfa of 4% to 6% (Combs, 2014).

TABLE 2 Physical properties of whole-plant corn processed using the shredding (SPr) or impact (IPr) processors

Treatments [1,2]	Whole-plant				Kernel fraction	
	Processing level index [3] (%)	Pilot-scale silo compacted dry basis density[4] (kg m^{-3})	Geometric-mean particle-size [5] (mm)	Fraction of mass >6.3 mm[6] (%)	Geometric-mean particle-size[7] (mm)	Fraction of mass <6.3 mm[8] (%)
CHP	33.0c	319c	8.6a	78a	4.1a	51b
SPr–1X	47.1b		7.8a	42b	1.4b	95a
SPr–2X	66.7a		4.8b	31b	0.9b	99a
IPr–1X	63.7a	341b	4.6b	43b	0.8b	99a
IPr–2x	70.1a	379a	3.4b	31b	0.6b	99a
SEM[9]	1.59	2.6	0.52	2.50	0.17	1.3
p-value	<0.001	0.001	0.003	<0.001	<0.001	<0.001

[1] All treatments harvested with forage harvester using 13 mm theoretical-length-of-cut. Average crop DM content was 448 g kg^{-1}. DM content was not significantly different across treatments.

[2] Treatments are chopped (CHP); processed using the shredding processor either one or two times (SPr-1X and SPr-2X) and processed using the impact processor either one or two times (IPr-1X and IPr-2X). $n = 3$ for each treatment.

[3] Processing level index based on treatment leachate conductivity–see equation no. 1.

[4] Data not available for the SPr treatments.

[5] Geometric-mean particle-size based on screening following ASABE Standard S424.1.

[6] Fraction of mass residing on top three screens (i.e., fraction over 6.3 mm) of ASABE S424.1 screener.

[7] Geometric-mean particle-size based on screening following ASABE Standard S319.4.

[8] Fraction of mass residing below 6.3 mm screen.

[9] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < .05$ using Tukey's comparisons.

TABLE 3 Composition of wilted and ensiled alfalfa stems or whole-plants used for the in situ digestion experiment

Constituent	Stems[a,b]				Whole-Plant[a,b]			
(% of DM)	CHP	IPr–2X	SEM	*p*-value	CHP	IPr–2X	SEM	*p*-value
CP	16.2	15.1	1.68	0.679	21.4	21.7	0.89	0.844
ADF	45.0	46.3	3.17	0.781	36.9	33.8	1.98	0.325
aNDF	52.2	54.4	3.45	0.685	43.5	40.8	2.10	0.404
Ash	8.7	8.2	0.47	0.485	10	10	0.41	0.748

Abbreviations: ADF, acid detergent fibre; aNDF, neutral detergent fibre; CP, crude protein.

[a] Second cutting alfalfa stems (~80% bloom) or third cutting whole-plant alfalfa (~10% bloom).

[b] Treatments are chopped (CHP) or processed using the impact processor two times (IPr-2X). $n = 3$ for each treatment.

4 | DISCUSSION

4.1 | Processing experiments

Inadequate fibre length can result in erratic DM intakes, decreased milk yields, lowered milk fat production and animal health problems (Krause & Oetzel, 2006). Recommendations for appropriate fibre length of an individual ration ingredient vary depending on the proportion and type of the remaining ingredients. It is recommended that 45% to 75% of alfalfa haylage particle reside on or above an 8 mm screen (Heinrichs & Kononoff, 2013). Although 53% of the whole-plant alfalfa particles resided on or above the 6.3 mm screen (Table 1), it is unknown if this material would provide adequate effective fibre in a ration mixed with other common ingredients. Further research should be conducted to determine if desired processing level and fibre length can both be achieved, for instance by chopping at a longer TLOC prior to processing.

Processing wilted whole-plant alfalfa resulted in a 11.4% point drop in PLI compared with processing unwilted crop (Table 1). As the crop dries, the cells become less turgid (Loper, 1972) and the stem gains mechanical strength (Galedar et al., 2008). These physical changes make it more difficult to achieve a given level of physical disruption compared with processing fresh alfalfa. Nonetheless, processing wilted material with the IPr still achieved the desired PLI of greater than 60% although two passes were required (Table 1).

Shredding wilted alfalfa improved initial density and fermentation quality of silages while reducing overall fermentation losses (Samarasinghe et al., 2019). Processing wilted alfalfa resulted in significantly greater compacted density in pilot-scale silos (Table 1). Further research should be conducted to determine if these results

TABLE 4 Coefficients for fractional rate of in situ disappearance and degradation of alfalfa stems or whole-plant alfalfa DM and NDF

	Stems[a,b]				Whole-Plant[a,b]			
Item[c]	CHP	IPr−2X	SEM	*p*-value	CHP	IPr−2X	SEM	*p*-value
DM, %								
A	19.6	22.5	0.30	0.090	22.6	31.0	0.17	0.015
B	35.4	34.7	0.20	0.140	53.1	46.0	0.35	0.005
C	45.1	41.9	0.11	0.030	24.3	23.0	0.36	0.210
Lag, h	1.3	0.0	0.14	0.020	0	0		
k_{d1}, h^{-1}	0.0462	0.0473	0.0083	0.670	0.0639	0.0609	0.00152	0.300
DM_{degrad}	34.9	37.6	1.3	0.010	50.0	54.1	0.34	0.013
NDF, %								
A	3.40	2.16	0.334	0.120	−3.74	0.21	0.591	0.042
B	35.1	36.1	0.71	0.270	52.3	49.3	0.23	0.037
C	61.5	61.8	0.49	0.260	51.5	50.5	0.81	0.530
Lag, h	1.4	2.0	0.28	0.270	3.0	2.1	0.39	0.230
k_{d1}, h^{-1}	0.0279	0.0334	0.0063	0.270	0.0361	0.0436	0.00349	0.150
NDF_{degrad}	14.4	14.9	1.57	0.130	15.9	20.9	0.61	0.078

[a] Second cutting alfalfa stems (~80% bloom) or third cutting whole-plant alfalfa (~10% bloom).

[b] Treatments are chopped (CHP) or processed using the impact processor two times (IPr-2X). *n* = 4 for each treatment.

[c] A is the rapidly soluble fraction (%); B is the slowly degradable fraction (%); C is the undegradable fraction (%); k_{d1} is the rate of ruminal degradation (h^{-1}); and k_p is the rate of passage assumed here as 0.060 h^{-1}. See Equations 3 and 4.

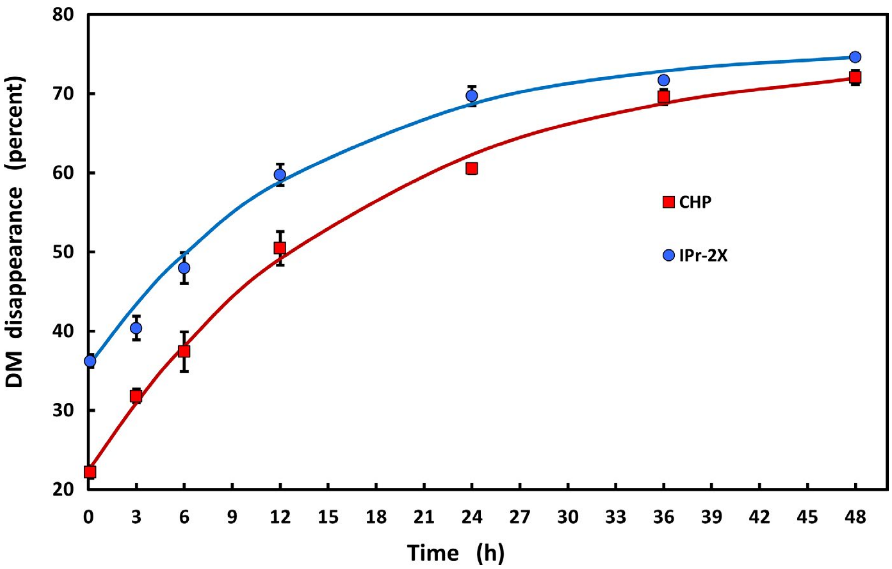

FIGURE 5 In situ dry matter disappearance versus time for chopped (CHP) or processed (IPr-2X) whole-plant alfalfa. Processing level index (PLI) for CHP and IPr-2X were 12.4% and 65.6%, respectively (see Table 1). Error bars represent standard error and *n* = 4

translate to improved density and fermentation in bunk and bag silos.

It is recommended that 45% to 65% of WPC particles reside on or above an 8 mm screen (Heinrichs & Kononoff, 2013). The SPr-2X and the IPr-2X treatments did not meet this recommended minimum mass fraction longer than 8 mm (Table 2). This may have been due to the large reduction in the kernel particle-size. In the future, it may be more instructive to make WPC particle-size recommendations for the stover and grain fractions separately rather than whole-plant recommendations.

Impact processing appeared to be the approach that warrants further research effort. Processing by shredding did not produce the desired level of processing as quantified by the PLI. Compared with an impact processor, the SPr has more components, requires more precision machining to fabricate and requires very small clearances which can be difficult to maintain in practice (Shinners et al., 2000). A processing concept that combines both impact and shredding could also warrant further research. Specific energy requirements and throughput capacity need to be investigated because it is known that impact processing of crop materials is energy intensive. Finally, a thorough economic analysis of the process from harvest through storage and animal performance will be required to fully understand the potential of improving DM and fibre digestion through intensive mechanical processing.

TABLE 5 Ruminal in situ digestion parameters for alfalfa stems or whole-plant alfalfa using aNDF and ln-linear model (Equation 7) plotted over two different incubation periods

		Over 48 h incubation time			Over 120 h incubation time		
		Disappearance rate constant (k_{d2})[c]			Disappearance rate constant (k_{d2})[c]		
Treatment[a]	Crop Material[b]	(h^{-1})	Intercept	R^2	(h^{-1})	Intercept	R^2
CHP	Stems	0.0294	4.70	0.971	0.0275	4.66	0.994
IPr-2X	Stems	0.0389	4.68	0.982	0.0324	4.58	0.987
CHP	Whole-plant	0.0315	4.61	0.983	0.0215	4.43	0.952
IPr-2X	Whole-plant	0.0373	4.61	0.997	0.0350	4.56	0.998

[a] Treatments are chopped (CHP) or processed using the impact processor two times (IPr-2X). *n* = 4 for each treatment.

[b] Second cutting alfalfa stems (~80% bloom) or third cutting whole-plant alfalfa (~10% bloom).

[c] k_{d2} (h^{-1}) is the slope which represents the fractional rate of disappearance of pdNDF. See Equation 7.

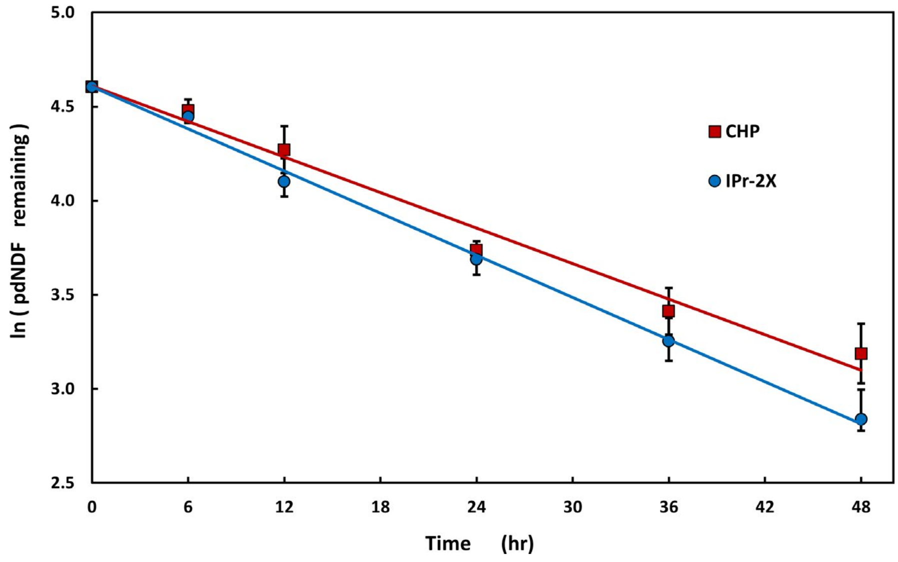

FIGURE 6 In situ digestion of ln pdNDF versus time for chopped (CHP) or processed (IPr-2X) whole-plant alfalfa. Processing level index (PLI) for CHP and IPr-2X were 12.4% and 65.6%, respectively (see Table 1). Error bars represent standard error and *n* = 4

4.2 | In situ digestion experiments

Processing by impact or shredding significantly affected the physical form of wilted whole-plant alfalfa, wilted alfalfa stems and WPC. The greater PLI implied that these treatments had greater surface area and cell rupture, which contributed to a greater alfalfa DM and pdNDF degradation. Increased surface area available for rumen microbial attachment was hypothesised as the reason for increased digestibility and animal performance of macerated fresh alfalfa (Hintz et al., 1999). Further research is needed to determine whether these benefits can contribute to improved animal performance, specifically dairy cattle milk production. Forage particle size can affect feed intake and milk production of dairy cows, but its effects depend upon type of forage and quantity of that forage in diet (Nasrollahi et al., 2015). Hall and Mertens (2017) noted that reducing forage particle size should reduce fibre volume and increase rate of passage, potentially increasing intake. However, they noted that increasing rate of passage can also reduce fibre digestibility. Previous research on effects of particle-size focussed solely on chopped forages rather than material by shredding or impact. Processing significantly reduced alfalfa haylage particle-size, so further information is needed to determine how to formulate a TMR ration with this material so that there is sufficient physically effective fibre (peNDF).

5 | CONCLUSIONS

This research demonstrated that intensive mechanical processing of wilted forages increased specific surface area and cell rupture as quantified by a leachate conductivity metric. The highly fibreized material was more compliant, resulting in improved compacted density. The process increased the rapidly soluble fraction and the rate of DM and pdNDF degradation of wilted alfalfa. Intensive mechanical processing has the potential to improve ruminant animal utilisation of forage crops through improved fibre digestion. Processing through impact, rather than through shredding, produced greater physical disruption.

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AUTHOR CONTRIBUTION

David Pintens: Conceptualization (equal); Formal analysis (equal); Investigation (equal); Writing – original draft (equal). Kevin Shinners: Conceptualization (lead); Formal analysis (lead); Funding acquisition (lead); Methodology (equal); Supervision (lead); Writing – review & editing (lead). Joshua Friede: Investigation (equal); Supervision (equal). Kenneth Kalscheur: Conceptualization (equal); Formal analysis (equal); Investigation (equal); Writing – review & editing (equal). Matthew Digman: Writing – review & editing (equal). Dave Combs: Conceptualization (equal); Methodology (equal).

DATA AVAILABILITY STATEMENT

No data is available.

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