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Impact—Shredding Processing of Whole-Plant Corn: Machine Performance, Physical Properties, and In Situ Ruminant Digestion

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Abstract: An intensive processing mechanism that combined impact and shredding was applied to create physical disruption of whole-plant corn as a means to increase in situ dry matter (DM) digestion in lactating dairy cows. A ratio of treatment leachate conductivity relative to that of an ultimately processed treatment, defined as a processing level index, was used to quantify material physical disruption. Two processing levels were compared to a control treatment, which applied conventional chopping and kernel processing. The non-grain fraction was substantially size-reduced by processing such that only 28% to 51% by mass of this material remained greater than 6.4 mm length. After processing with the experimental processor, greater than 85% of kernels passed through a 4.75 mm screen, and the corn silage processing score (CSPS) was 18 to 27 percentage points greater than the control. The highly fiberized material was more compliant; thus, compacted density was 9% to 17% greater than the control. During in situ digestion experiments, processing significantly increased the rapidly soluble DM fraction by 10 percentage points and the extent of DM disappearance by 5 percentage points through 16 h incubation.

Keywords: corn; digestion; fiber; hammermill; impact; particle size; processing; ruminant; shredding

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1. Introduction

At harvest, whole-plant corn (WPC) is typically processed using an on-board kernel processor featuring a pair of closely spaced toothed rolls operating at differential speeds. The main goal of processing in this fashion is to size reduce the grain fraction, hence the term “kernel processor”. The corn kernel pericarp protects the endosperm, and the pericarp is highly resistant to rumen microbial attachment and enzymatic digestion if it is left intact [1]. Processing breaks the seed coat, creating greater starch surface area, and ruminant starch digestion is enhanced [2]. The fraction of total starch that passes through a 4.75 mm sieve is defined as the Corn Silage Processing Score (CSPS), with an optimal score of at least 70% [3]. The efficacy of current kernel processing as quantified by the CSPS is often variable, influenced by both crop factors and harvester configuration. Salvati et al. [4] reported that 38% of United States Midwest producers surveyed were not achieving the optimum CSPS score.

Although processing WPC with a kernel processor improves starch utilization, its use has shown to have variable impact on the digestibility of the fiber fraction [5–8]. Research has shown that fiber digestibility was not significantly improved or even decreased when WPC was processed with conventional kernel processors [9,10]. Corn stalks are structurally strong [11] with high lignin content, and thus, processing by shredding them with a conventional kernel processor may not create enough improvement in the specific surface area to affect fiber digestion [6]. One potential way to improve the utilization of the fiber fraction of WPC is through new processing mechanisms that dramatically change the physical form of not only the grain fraction but also the non-grain fractions of WPC. This is the focus of this research.

Any new mechanism to change the WPC physical properties should increase the specific surface area of the non-grain fractions without excessive particle size reduction of the fiber fraction. Physically effective NDF (peNDF) is the fraction of fiber that stimulates chewing activity. It is primarily related to particle size and promotes rumination and saliva production [12]. The most effective way to increase WPC peNDF using current technology is to increase the theoretical length of the cut at harvest, but this can lead to reduced CSPS [7], reduced harvester throughput and shortened processor roll life. Alternatives to the conventional roll processors should be explored that produce greater WPC digestion, maintain fiber length, and consistently provide optimal CSPS.

This work focused on a new method of improving WPC digestion by a novel mechanical processing technique using impact and shredding. Our first hypothesis was that processing by impact and shredding would substantially alter the physical properties of not only the grain fraction of WPC, but also the fiber fraction. An additional hypothesis was that these physical changes would improve in situ DM digestion in ruminant dairy cows. The specific objectives were to: (a) modify a hammermill to process WPC through a combination of impact and shredding; (b) quantify the physical properties of processed WPC as affected by crop maturity, number of processing operations, processor configuration, and process timing; and (c) quantify the compositional, fermentation, and in situ digestion of WPC silage that was processed prior to ensiling.

2. Materials and Methods

2.1. Impact–Shredding Processor

Greater physical disruption of forage crops was obtained through a combination of impact and shredding than by shredding alone [13]. Therefore, to process WPC by both impact and shredding, a screenless hammermill was developed (Figure 1). Disruption of the plants' physical structure occurred by impact with the high-speed hammers with some additional attrition by shredding as the material was dragged along the roughened surface of the scroll. The experimental impact–shredding processor had a 50 cm wide rotor featuring three rows of hammers each with 22 free swinging hammers that were 4 mm thick and spaced 19 mm apart. The traced radius of the hammers was 25 cm, and the radial clearance between the scroll and the hammers was 10 mm. The peripheral speed of the hammers was generally 80 m$\cdot$s^{-1}, except for experiments where rotational speed of the rotor was varied (see Section 2.7). A scroll without openings replaced the typical hammermill screen. Input flow of chopped material occurred tangentially into the path of the hammers where, after impact, it was dragged along the scroll through an arc of 180 degrees before exiting tangentially (Figure 1). To facilitate shredding, the scroll featured a roughened diamond plate surface (part number 3DRW1, Grainger, Chicago, IL, USA). The rotor was powered by a John Deere (Moline, IL, USA) model 7235R tractor through a belt drive that increased rotor speed to a maximum of 3056 rev$\cdot$min^{-1} when the tractor PTO was operated at 1100 rev$\cdot$min^{-1}. Material recirculation was not observed, and thus, the time to traverse the 0.785 m arc from the input to the exit was less than 0.01 s at the hammer tip speed of 80 m$\cdot$s^{-1}. The mechanism was stationary, and material was brought to it for processing.

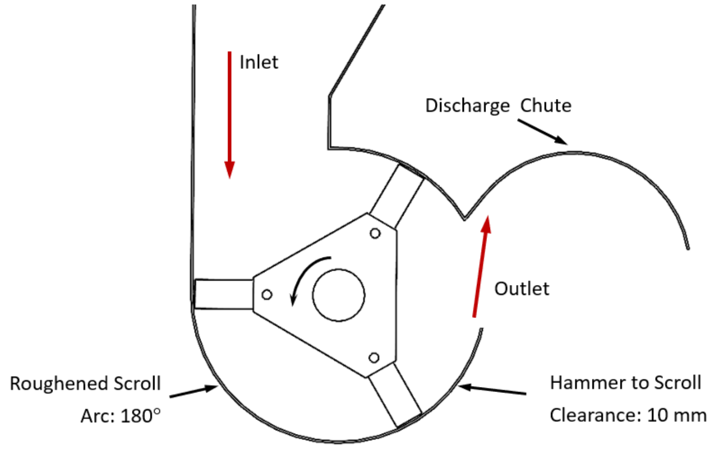

Figure 1. Schematic of impact–shredding processor.

2.2. Experiments Conducted

A total of seven experiments related to processing performance were conducted (Table 1). These experiments were conducted to test the hypothesis that processing by impact and shredding changed important physical properties of both the grain and fiber fraction of WPC. These experiments determined how processing level was affected by crop maturity, processor configuration, and process timing (i.e., pre- or post-storage). An additional experiment was conducted to examine the hypothesis that impact–shredding processing changed the in situ DM digestion of WPC in ruminant dairy cows.

Table 1. Details of experiments conducted during 2020 using whole-plant corn.

Experiment Number	Harvest and Processing Date	Processing Treatments	Days Since Planting [a, b]	Approximate Kernel Maturity	Whole-Plant Dry Matter	Mass-Flow into Processor
					(g·kg^{-1})	(Mg WM·h^{-1})
1	27-Aug	UP, KP, 1X and 2X	121	1/4 to 1/3 milk line	365	57
2	2-Sep	UP, KP, 1X and 2X	127	1/3 to 1/2 milk line	352	59
3	11-Sep	UP, KP, 1X and 2X	136	1/2 to 2/3 milk line	363	57
4	15-Sep	UP, KP, 1X and 2X	140	3/4 to full milk line	381	58
5	17-Sep	UP, 1X and 2X	142	Full milk line	346	94
6	21-Sep	UP, KP and 1X	146	Full milk line	447	84
7	25-Sep	UP, KP, 1X and 2X	154	1/2 to 2/3 milk line	361	57

[a] Experiments 1–6 used Renk RK717SSTX with 105-day comparative relative maturity (CRM) planted on 28 April.
[b] Experiment 7 used Dairyland DS-4816AMXT with 108-day CRM planted on 24 April.

Four treatments were investigated in most experiments: chopped but unprocessed (UP), and UP material that was subsequently processed once or twice with the experimental processor (1X and 2X, respectively). The fourth treatment, which served as the control, was chopped and processed with the harvester's on-board kernel processor (KP) (see Section 2.4). In all experiments, there were three replicates per treatment, and treatments were created in random order.

2.2.1. Impact of Crop Maturity

Experiments 1–4 were conducted to investigate the effect of using the experimental processor across different WPC maturities. This was accomplished by harvesting and processing in a similar fashion but on four different days over a 20-day period.

2.2.2. Specific Energy Requirements and Rotor Speed

Experiments 5 and 6 were conducted to quantify the specific energy requirements of processing. In the latter experiment, three different processor peripheral speeds were used (51, 65 and 80 $m \cdot s^{-1}$) (see Section 2.7).

2.2.3. Chop Length

It was observed that processing with the experimental processor considerably reduced the material particle size. Therefore, Experiment 7 was conducted using 100 mm theoretical length of cut (chop length) to determine if the final particle size of the processed whole plant could be increased by doubling the initial chop length (50 mm was used in Experiments 1–6) of the UP material used to create the 1X and 2X treatments.

2.3. Additional Investigations

2.3.1. Process Timing

Processing by impact and shredding was considered as an alternative to the kernel processor currently used on forage harvesters. However, processing with the experimental processorcould alternatively occur after ensiling and just prior to feeding. This alternative process timing was investigated using material harvested during Experiment 1. To create fermented material for post-storage processing, three additional replicates of UP material were placed into 19 L plastic containers, compacted using the procedure described in Section 2.5, and then sealed. This material was stored indoors for 81 days. After storage, the fermented contents of the three replicate containers were removed, consolidated, and homogenized by hand mixing. The homogenized material was then halved by mass and further subdivided into three replicates per treatment, which were then processed in the experimental processor either once or twice (1X or 2X).

2.3.2. Processing of Plants without Ears

Processing as investigated here changed the physical properties of both the kernel and non-grain fractions of the plant. To investigate the impact of processing on just the stalk and leaves, additional crop treatments were created during Experiments 4 and 7. These were created by removing the ears by hand prior to chopping. Using this material, additional UP, KP, 1X, and 2X treatments were created as described above.

2.4. Harvest Procedure

Details of the WPC crop used in all experiments is provided in Table 1. For all experiments, WPC was harvested using a New Idea (Coldwater, OH, USA) model 6200 forage harvester. Average stubble height was 27 cm. Except where noted, the unprocessed WPC that was subsequently processed in the experimental processor was chopped at 50 mm chop length. For the KP treatment, WPC was chopped at 25 mm chop length and then processed with the forage harvesters on-board roll-type kernel processor operating at 15% speed differential with 2 mm roll gap. Except when power requirements were measured (see Section 2.7), the stationary processor was fed with a 28 cm wide by 5.5 m long conveyor. Typical mass-flow rate into the processor is provided in Table 1.

2.5. Properties Quantified

Each replicate for all treatments and experiments generated approximately 20 kg wet matter (WM) of material from which sub-samples were randomly collected to quantify various material properties. For all experiments, two 400 g WM sub-samples per replicate were collected by hand to determine DM content by oven drying at 105 °C for 24 h in accordance with ASABE Standard S358.3 [14]. An additional sub-sample per replicate of approximately 6 L was collected by hand to determine whole-plant geometric mean particle size using procedures described in ASABE Standard S424.1 [15].

Additional sub-samples of approximately 850 g WM per replicate were collected by hand to quantify kernel particle size. These sub-samples were oven dried for 12 h at

55 °C, and then, the kernel fraction was separated from the non-grain material by a water separation procedure described in [16]. Savoie et al. [16] reported that more than 92% of kernels were separated from the stover using this technique. 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 eight screens (9.53, 6.35, 4.75, 3.35, 2.36, 1.70, 1.19, and 0.59 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. The kernel particle size was determined using equations found in ASABE Standard S319.4 [17].

From the approximate 20 kg WM generated per replicate, approximately 9.0 kg WM was used to quantify compacted density. Material was placed into a plastic tube (25 cm inside diameter, 62 cm height, 30 L volume) and compressed with a hydraulic cylinder, which applied force to a 25 cm diameter platen. Pressure applied by the platen on the face of the material was 140 kPa, controlled by a relief valve in the hydraulic circuit. Cylinder extension was halted automatically when relief valve actuation occurred. With the hydraulic cylinder stationary in the final position, the height of the compacted material was measured by hand to the nearest 1 cm so that the volume and density could be calculated.

Leachate conductivity (LC) was used to quantify the level of crop processing using a procedure first developed by Kraus et al. [18]. The first step to determine LC involved using a microwave oven to determine DM content using procedures described in ASABE Standard S358.3 [14]. The DM was then used to determine the wet mass needed to create 5 g DM sub-samples from each replicate. Each sub-sample was individually placed in a 600 mL glass container and 300 mL of distilled water added. An orbital shaker table operated at 180 cycles·min^{-1} was used to mix the material for 1 min. After mixing, the contents were then filtered through two layers of cheesecloth and the conductivity of the leachate immediately measured using a Thomas Scientific (Swedesboro, NJ, USA) model 4366 conductivity meter. To maintain balance on the shaker, two duplicate samples per replicate were simultaneously analyzed in this manner. A normalizing treatment defined as the ultimate possible level of mechanical processing, and hence the maximum LC, was used the compare processing across treatments and experiments. To create this treatment, the shaking step was replaced by processing the mixture in a model KB64 Vanaheim blender (City of Industry, CA, USA) for 1 min at no-load speed of 28,000 rev·min^{-1}. The LC was then measured as described above. Four blender replicates were created during each experiment. The ratio of the treatment LC_{tr} to the blender (i.e., "ultimate") treatment LC_{bl}, expressed as a percent, was defined as the processing level index (PLI):

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

2.6. Kernel Leachate Conductivity

Initial results had shown that processing with the experimental processor increased the LC and PLI and decreased both the whole-plant and kernel particle size. Greater release of ions into the leachate could have been the result of greater surface area of the kernel or the non-grain fractions of the plant. To quantify the effect of kernel particle size on LC, additional procedures were carried out on extra 1X material created during Experiment 4. The kernel and stover fractions were separated by differences in terminal velocity using a vertical tube air separation device [19]. This technique was used rather than water separation described in Section 2.5 so that the subsequent LC would not be affected by the loss of water-soluble constituents to the effluent during separation. The separated kernel fraction was then classified by size using the screening process described in Section 2.5. This process resulted in the following classifications: material from the (a) 6.54 mm screen; (b) 4.75 and 3.35 mm screens; (c) 2.36 and 1.70 mm screens; and (d) the remaining screens and pan. The LC of 5 g DM of each of these four classifications was then determined for eight replicates per size classification using techniques described in Section 2.5.

2.7. Specific Energy Requirements

Experiment 5 was conducted to quantify the power required for processing 1X or 2X when processor speed was 80 m·s^{-1}. Experiment 6 was conducted to investigate the power required for processing 1X but at 51, 65 and 80 m·s^{-1}. These processor speeds were attained by varying input PTO speed at 700, 900 and 1100 rev·min^{-1}. A self-unloading forage wagon was used to collect UP material chopped at 50 mm chop length. After chopping, material was deposited from the forage wagon into the silo blower, which fed the processor. The mass processed per replicate was determined using load cells on the forage wagon. Typical mass processed per test was 450 kg WM, and each treatment was replicated three times. The rate of fuel use was recorded during each replicate test from the tractor's controller area network (CAN) bus with a USB to CAN adapter (ECOM, EControls, San Antonio, TX, USA) 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 (San Antonio, TX, USA) CANCapture Version 3.5 software. Prior to these experiments, engine fuel use was recorded in this manner at PTO speeds of 700, 900, and 1100 rev·min^{-1}, while the tractor's PTO was loaded from 11 to 130 kW in nine equal increments using a PTO dynamometer (model NEB400, AW Dynamometer, Pontiac, IL, USA). Using these data, linear equations were developed to predict tractor PTO power from CAN fuel rate (R^2 = 0.99) at each PTO speed. The mass processed per test divided by processing time was used to calculate the mass-flow. Dividing the PTO power by mass-flow rate provided the specific energy required.

2.8. Fermentation Properties

In Experiments 1–4, an additional sample of approximately 230 g DM per replicate was used to fill polyethylene vacuum pouches and the air evacuated using a vacuum sealer (Minipak, Friulmed, Monfalcone, Italy). This material was removed from storage after 96, 90, 81 and 75 days in storage. The 12 total vacuum bags per treatment (4 experiments × 3 replicates) were combined and homogenized. Five replicate sub-samples of approximately 385 g DM each were then created for each treatment. These samples were subsequently analyzed for crude protein (CP), neutral detergent fiber (NDF), and starch (using NIRS techniques) and pH, fermentation products, and CSPS (using wet laboratory techniques). All analyses were performed by Rock River Laboratories (Watertown, WI, USA) using their standard methodology.

2.9. Rumen Degradation

Rumen DM degradation characteristics of the KP, 1X, and 2X treatments were quantified using the remaining homogenized material described in Section 2.8. An in situ technique was used that preserved the physical form of the samples, i.e., samples were placed in the rumen bags in their "as-fed" physical form, not dried and ground as typically used for in situ digestion research. This technique was successfully used by Johnson et al. [10]. Individual samples of wet material equaling 9.0 g DM were weighed into mesh bags (25 × 35 cm, 50 µm pore size). A total of 225 samples (3 treatments × 5 replicates × 3 cows × 5 time points) were prepared. Each time point (3, 7, 16, 24, and 120 h) was incubated separately because the large size of samples limited the ability to run all time points concurrently. At each time point, fifteen samples (3 treatments × 5 replicates per treatment) were placed into each of three separate mesh laundry bags, which were individually placed in three different lactating dairy cows with rumen cannulas. After incubation, the residues from the three cows were combined prior to analyses to mitigate cow-to-cow variation. The cows were milked twice daily and fed a diet consisting of corn silage, alfalfa haylage, and concentrate.

At the appropriate time intervals, sample bags were removed from the rumen and immediately placed in ice water to terminate microbial activity. The samples were then rinsed in a commercial washing machine using two 5 min rinse cycles. Washed samples were then dried in a forced-air oven for 24 h at 60 °C and weighed to determine DM disappearance. An additional set of 15 samples was prepared, as described above, to determine 0 h digestibility (i.e., the rapidly soluble fraction). These samples were soaked in warm water (approximately 40 °C) for 20 min and then rinsed, dried, and weighed as described above. Ruminal disappearance of DM was expressed as a fraction of the original sample DM amount:

$$\mathrm{Rum_{Disp}} = \frac{(\mathrm{M_t} - \mathrm{M_{res}})}{\mathrm{M_{tot}}} \quad (2)$$

where M_t was the dry mass at any time point t, M_{res} was residual dry mass at 120 h, and M_{tot} was the total initial dry mass.

2.10. Statistical Analysis

Factorial analysis using the Standard Least Squares option in the Fit Model platform of JMP Pro (ver. 15, SAS Institute Inc., Cary, NC, USA) was used to conduct the statistical analysis. The investigations of processing treatment effect on processing level (PLI); whole-plant and kernel particle size; energy requirements; fermentation properties; and in situ DM disappearance at each of the six time points were all analyzed as separate one-way ANOVAs. The one-way ANOVAs were analyzed using the model:

$$Y_{ij} = \mu + T_i + E_{ij} \quad (3)$$

where μ is the overall mean, T_i is the processing treatment (UP, KP, 1X, or 2X), and E_{ij} is the residual error.

The investigation of differences due to processing treatment and harvest date (see Section 2.2.1) were analyzed using a two-way ANOVA. The investigation of processing occurring either pre- or post-ensiling (see Section 2.3.1) was also analyzed using a two-way ANOVA. The two-way ANOVAs were analyzed using the models:

$$Y_{ijk} = \mu + T_i + D_j + (T \times D)_{ij} + E_{ijk} \quad (4)$$

$$Y_{ijk} = \mu + T_i + P_j + (T \times P)_{ij} + E_{ijk} \quad (5)$$

where μ is the overall mean, T_i is the processing treatment (UP, KP, 1X, or 2X), D_j is the harvest date, P_j is when processing took place (i.e., pre- or post-ensiling), $(T \times D)_{ij}$ is the interaction between processing treatment and harvest date, $(T \times P)_{ij}$ is the interaction between processing treatment and process timing, and E_{ijk} is the residual error.

All least square means were compared using Tukey's test or Student's *t* test as appropriate. Significant differences were declared at $p \leq 0.05$, and tendencies were considered at $0.05 \leq p \leq 0.10$.

3. Results

3.1. Harvest Date

Although harvest date, and by inference crop maturity, had a statistically significant (p = 0.002) impact on the PLI of processed WPC, the differences between harvest dates were small and unlikely to be biologically significant. For instance, the PLI for the 2X treatment was 65%, 68%, 68% and 69% (p = 0.044), respectively, across the four harvest dates used in Experiments 1–4 (Table 2). Compacted density was not significantly different across harvest date (p = 0.147). Average whole-plant (p = 0.006) and kernel (p = 0.010) particle size were statistically different across the harvest dates, but again, differences were small. For instance, the whole-plant particle size for the 1X treatment was 10, 7, 7 and 8 mm (p = 0.006), respectively, across the four harvest dates in Experiments 1–4 (Table 3). Kernel particle size for the 1X and 2X treatments varied by no more than 0.3 mm across harvest dates in Experiments 1–4 (Table 4).

Table 2. Processing level index (PLI) for whole-plant corn or corn plants without ears.

Process Treatment [b]	**Whole-Plant**							**Plant without Ears** [a]
	Experiment No.							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**4**
	Processing Level Index (%)							
UP	29c	32c	29d	29d	31c	28b	27c	17c
KP	32c	36c	38c	36c		30b	31c	19c
1X	51b	54b	53b	56b	52b	48a	55b	47b
2X	65a	68a	68a	69a	64a		64a	62a
SEM [c]	1.2	1.0	1.4	1.3	1.6	1.2	1.0	1.2
p-values [c]	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[a] Ears were removed by hand prior to harvest. Material consisted of stalk and leaves that had an average DM content of 274 g·kg^{-1}. [b] Treatments were unprocessed (UP), processed with kernel processor (KP), and UP material processed through experimental processor once or twice (1X and 2X, respectively). [c] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

Table 3. Geometric mean particle size of whole-plant corn or corn plants without ears.

Process treatment [b]	**Whole-Plant**							**Plant without Ears** [a]	
	Experiment No.								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**4**	**7**
	Geometric Mean Particle Size (mm)								
UP	39a	27a	29a	34a	31a	24a	38a	69a	110a
KP	13b	19b	11b	13b		12b	11b	35b	26b
1X	10bc	7c	7c	8bc	9b	8b	10b	15c	22b
2X	6c	5c	5d	5c	5c		6b	8d	11b
SEM [c]	1.5	1.5	0.4	1.4	1.0	0.9	2.0	0.8	5.5
p-values [c]	< 0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Fraction of mass residing on or above 6.4 mm screen (%)								
UP	64a	53a	56a	57a	57a	47a	56a	87a	87a
KP	30b	38b	31b	37b		30b	27b	74b	60b
1X	26b	19c	23c	27c	27b	25c	27b	45c	51c
2X	18c	12c	12d	16d	15c		17c	28d	34d
SEM [c]	1.7	2.0	1.0	1.1	1.6	0.9	1.9	0.6	0.9
p-values [c]	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[a] Ears were removed by hand prior to harvest. Material consisted of stalk and leaves that had an average DM content of 274 and 263 g·kg^{-1} for Experiments 4 and 7, respectively. [b] Treatments were unprocessed (UP), processed with kernel processor (KP), and UP material processed through experimental processor once or twice (1X and 2X, respectively). [c] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

Table 4. Geometric mean particle size of the kernel fraction.

Process Treatment [b]	Experiment No [a]					
	1	2	3	4	6	7
	Geometric Mean Particle Size (mm)					
UP	3.8a	3.7a	4.1a	4.0a	4.5a	4.7a
KP	3.1b	3.0b	3.2b	3.3b	3.3b	3.8b
1X	1.9c	2.0c	1.8c	2.1c	2.1c	2.0c
2X	1.5d	1.6c	1.4d	1.6d		1.4d
SEM [c]	0.08	0.13	0.05	0.05	0.10	0.11
p-values [c]	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Fraction of mass less than 4.75 mm (%)					
UP	48d	49c	45d	47d	41a	37d
KP	59c	66b	66c	65c	72b	54c
1X	85b	84a	86b	85b	85a	84b
2X	94a	94a	95a	94a		95a
SEM [c]	1.4	2.9	0.9	0.9	2.0	2.0
p-values [c]	<0.001	<0.001	<0.001	< 0.001	<0.001	<0.001

[a] Data not available for Experiment 5. [b] Treatments were unprocessed (UP), processed with kernel processor (KP), and UP material processed through experimental processor once or twice (1X and 2X, respectively). [c] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

3.2. Leachate Conductivity and Processing Level Index

It was observed that 1X and 2X processing resulted in considered physical disruption to WPC. The stalks were shredded longitudinally, the cobs broken, and the kernels greatly size reduced (Figure 2). Consequently, the PLI was consistently different between treatments (Table 2). Processing WPC with an on-board kernel processor is the current conventional practice. Across all experiments, processing UP material with the on-board kernel processor (control KP treatment) only increased the PLI by 5 percentage points (Table 2). In these same experiments, the PLI was 24 and 37 percentage points greater than the UP treatment when this material was processed 1X or 2X, respectively (Table 2). The additional processing operation (2X vs. 1X) increased whole-plant PLI by 13 percentage points. Increasing the chop length from 50 mm (Experiments 1–6) to 100 mm (Experiment 7) did not appreciably change the resulting PLI of the 1X and 2X treatments. At 100 mm chop length, the PLI of the 1X and 2X treatments were 24 and 33 percentage points greater than the KP treatment, similar to when the chop length was 50 mm.

Figure 2. Whole-plant corn (after ensiling) processed with an on-board kernel processor (left—KP treatment) or with the experimental processor either once (middle—1X treatment) or twice (right—2X treatment). Processing took place prior to ensiling.

Processing altered the physical properties of the kernel and non-grain fractions, with both contributing to the greater release of ions to the leachate. In Experiment 4, the average LC for plants with and without ears processed 1X was 279 and 328 μS·cm^{-1}, respectively. Although the LC increased with decreasing kernel particle size (Figure 3), the LC of the kernel fraction (42 to 115 μS·cm^{-1}) was much less than that of the processed plants without ears (328 μS·cm^{-1}). The LC of the whole-plant was less than that of the plant without ears because the kernels with low LC diluted the overall LC from the rest of the plant.

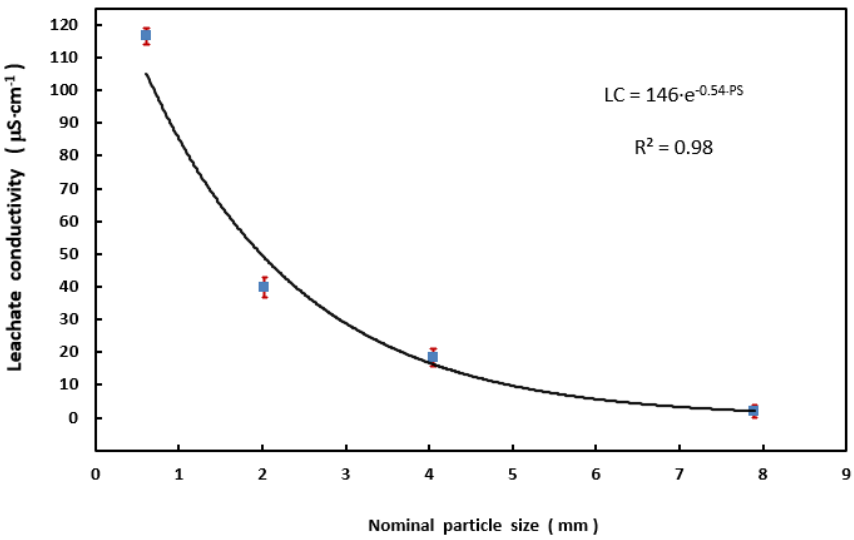

Figure 3. Leachate conductivity (LC) of the kernel fraction versus nominal kernel particle size (PS). Kernel fraction separated from 1X treatment in Experiment 4. Error bars represent the standard error and n = 8.

3.3. Particle Size

Processing 1X or 2X significantly reduced the whole-plant particle size compared to the parent material (UP) used to create the processed treatments (Table 3). Increasing the chop length from 50 mm (Experiments 1–6) to 100 mm (Experiment 7) did not create much improvement in the whole-plant particle size of the 1X and 2X treatments. In Experiments 4 and 7, the average fraction of material residing on or above the 6.4 mm screen was 56%, 32%, 27%, and 16% for whole-plants and 87%, 67%, 48%, and 31% for plants without ears for the UP, KP, 1X, and 2X treatments, respectively.

Processing 1X or 2X significantly reduced the kernel particle size compared to the parent material (UP) used to create the processed treatments (Table 4). The average kernel particle size of the 2X treatment was 55% smaller than the KP treatment. Across all experiments, the average fraction of kernels material residing below the 4.75 mm screen was 45%, 64%, 85%, and 94% for the UP, KP, 1X, and 2X treatments, respectively.

3.4. Compacted Density

Compared to the KP treatment, compacted DM density was 8% and 17% greater for the 1X and 2X treatments, respectively (Figure 4). When the 1X and 2X treatments were processed using UP material chopped at 100 mm length (Exp. 7), compacted dry basis density of these treatments (260 and 268 kg·m^{-3}, respectively) was significantly greater (p = 0.001) than the KP treatment chopped at 25 mm chop length (236 kg·m^{-3}).

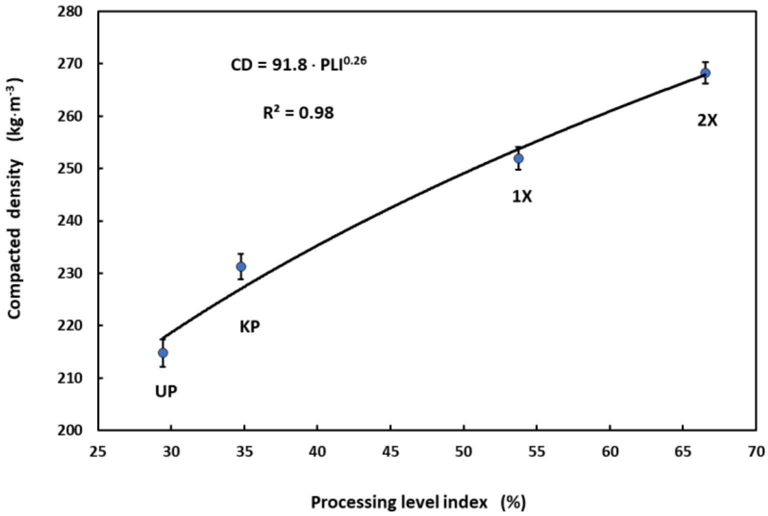

Figure 4. Dry basis compacted density (CD) of the whole-plant versus processing level index (PLI) for the UP, KP, 1X and 2X treatments. Averages from Experiments 1–4 and Experiment 7. Error bars represent the standard error and n = 15.

3.5. Specific Energy Requirements

Specific energy required for processing with the experimental processor ranged from 1.0 to 2.3 kW-h·Mg^{-1} and was 1.7 and 1.0 kW-h·Mg^{-1} for the 1X and 2X operations, respectively, when operated at the typical speeds (80 m·s^{-1}) and moistures used for most the experiments reported here (Exp. 5, Table 5). The energy requirements reported here represent those for each operation (1X or 2X) separately. The energy requirements for a second processing operation (2X) were significantly less than for the first (Exp. 5, Table 5). Increasing peripheral speed of the hammers from 51 to 80 m·s^{-1} increased energy requirements by 77% but only improved the PLI by 8 percentage points (Exp. 6, Table 5). Energy requirements were greater in Experiment 6 likely due to greater DM content (447 g·kg^{-1}) than in Experiment 5 (346 g·kg^{-1}).

Table 5. Specific energy requirements (on as-processed moisture basis) for processing whole-plant corn with the experimental processor during Experiments 5 and 6.

Experiment Number	Process Treatment [a]	Dry matter Content	Processing Level Index	Specific Energy
		(g·kg^{-1})	(%)	(kW·h·Mg^{-1})
Exp. 5	UP	330a	31c	
	1X	353a	52b	1.7a
	2X	356a	64a	1.0b
SEM [b]		12.4	1.6	0.11
p-values [b]		0.302	<0.001	<0.001
Exp. 6	UP	433bd	28c	
	KP	429c	30c	
	1X - 51 m·s^{-1}	457ab	40b	1.3b
	1X - 65 m·s^{-1}	457ab	45ab	1.8a
	1X - 80 m·s^{-1}	459a	48a	2.3a
SEM [b]		5.8	1.2	0.13
p-values [b]		0.001	<0.001	0.005

[a] Peripheral speed rotor was 80 m·s^{-1} for Experiment 5 and as noted in Experiment 6. Treatments were unprocessed (UP), processed with kernel processor (KP), and UP material processed through experimental processor once or twice (1X and 2X, respectively). [b] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

3.6. Process Timing

The PLI significantly increased for 1X and 2X treatments when processing took place post-ensiling (Table 6). Both lactic and acetic acid were produced during fermentation of the UP material (Table 7), and the electrical conductivity of solutions increases as the concentration of these acids increases [20,21]. At the time of post-ensiling processing, the lactic and acetic acid levels of the two processed treatments would have been the same because the 1X and 2X treatments were both created using ensiled UP material. Therefore, PLI differences across treatments would have been only due to differences in physical properties. Whole-plant particle size was not significantly different when comparing each treatment pre- or post-ensiled (Table 5). However, post-ensiling kernel particle size was significantly less than pre-ensiled kernel particle size across all treatments.

Table 6. Material properties of whole-plant corn processed either at harvest (Experiment 1) or after ensiling.

Process Timing	Process Treatment [a]	Whole-Plant			Kernel Fraction	
		Processing Level Index	Geometric Mean Particle-Size	Fraction of Mass on or above 6.4 mm Screen	Geometric Mean Particle-Size	Fraction of Mass Less than 4.75 mm
		(%)	(mm)	(%)	(mm)	(%)
At harvest [b]	UP	29e	39a	64a	3.8a	48d
	1X	51c	10b	26b	1.9c	85c
	2X	65b	6b	18c	1.5d	94a
After ensiling [b]	UP	42d	45a	67a	3.1b	54c
	1X	69b	11b	30b	1.3de	89b
	2X	79a	6b	15c	1.1e	96a
SEM [c]		1.1	1.9	1.4	0.08	1.1
p-values [c]		0.046	0.269	0.077	0.096	0.161
Averaged by process timing						
At harvest		48b	18a	37a	2.4a	76b
After ensiling		63a	20a	37a	1.8b	80a
SEM [c]		0.6	1.1	0.8	0.04	0.6
p-values [c]		<0.001	0.121	0.953	<0.001	0.001

[a] Treatments were unprocessed (UP) and processed through experimental processor once or twice (1X and 2X, respectively). [b] At harvest, processing took place on 27 Aug, and processing after ensiling took place 81 days later. [c] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's or Student's t test comparisons.

Table 7. Composition and fermentation products of whole-plant corn silage processed with three treatments. Processing took place prior to ensiling.

Process Treatment [b]	DM	Composition [a] (g·kg^{-1} DM)					Fermentation Products (g·kg^{-1} DM)			
	(g·kg^{-1})	CP [c]	NDF [c]	Starch	CSPS [c]	pH	Lactic Acid	Acetic Acid	Ethanol	Total Acids [d]
KP	386a	72b	357a	382a	68c	3.76a	48b	12a	10a	63b
1X	375a	76a	351a	372a	86b	3.80b	52ab	13a	8a	67ab
2X	377a	75a	368a	362a	95a	3.78ab	56a	13a	10a	72a
SEM [e]	5.6	0.5	10.0	18.4	0.6	0.004	2.0	0.5	1.7	2.5
p-values [e]	0.323	<0.001	0.501	0.758	<0.001	0.001	0.029	0.291	0.634	0.054

[a] Composite of treatments from Experiments 1–4 (Table 1) removed from storage after 96, 90, 81 and 75 days in storage, respectively. [b] Treatments were processed with kernel processor (KP) and processed through experimental processor once or twice (1X and 2X, respectively). [c] Crude protein (CP), neutral detergent fiber (NDF) and corn-silage processing score (CSPS) [3]. [d] Butyric, propionic, and succinic acids averaged less than 2 g·kg^{-1} DM and there were no significant differences between treatments. [e] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

3.7. Nutrient Content and Fermentation Analysis

There were no significant differences in NDF or starch content between treatments after ensiling (Table 7). The CP content was significantly less for the KP treatment. The CSPS was significantly different between all three treatments, with the CSPS increasing as the level of processing increased (KP to 1X to 2X). There were no significant differences between treatments for pH, acetic acid, or ethanol. The 2X treatment had significantly greater lactic acid and total acids compared to the KP treatment.

3.8. Rumen Digestion

The rapidly soluble DM fraction (i.e., 0 h time point) was significantly greater for the 1X and 2X processed material than for the KP material (Figure 5, Table 8). Early (i.e., 3 and 7 h) in situ DM disappearance was greater for both the 1X and 2X treatments compared to the KP treatment, and the 2X DM disappearance was greater than the KP at 16 and 24 h (Table 8).

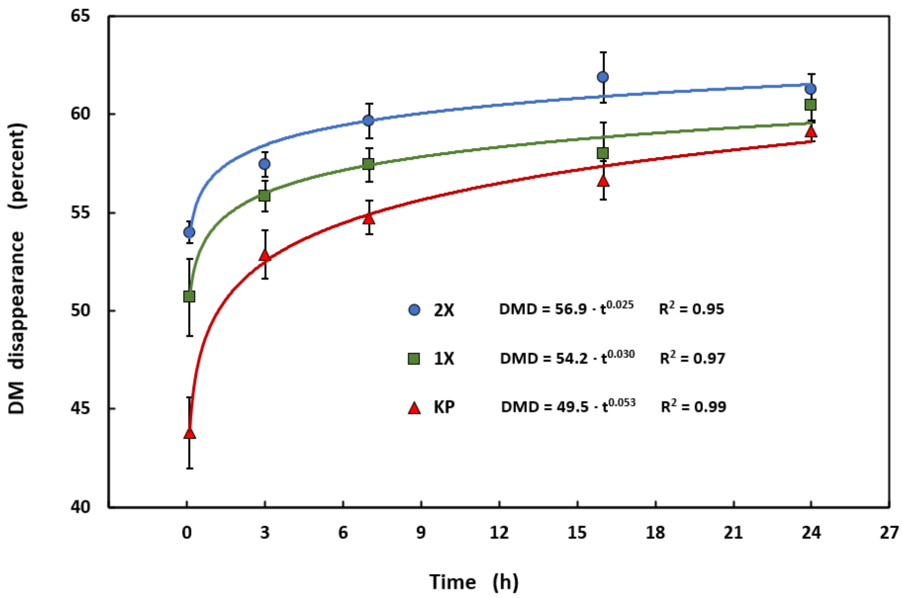

Figure 5. In situ dry matter disappearance (DMD) versus time (t) for whole-plant corn silage. Processing took place prior to ensiling. Processing level index (PLI) for KP, 1X and 2X treatments averaged 36%, 54% and 67%, respectively. Error bars represent standard error and n = 5.

Table 8. In situ dry matter disappearance of whole-plant corn silage at each of the six time points (n = 5). Treatments were processed prior to ensiling.

Processing Treatment [a]	0 h	3 h	7 h	16 h	24 h	120 h
KP	43.8c	50.9c	54.7c	56.7b	59.2b	73.8a
1X	50.7b	55.7b	57.7b	58.0ab	60.4ab	74.4a
2X	54.0a	57.5a	59.7a	61.9a	61.3a	75.2a
SEM [b]	1.53	0.71	0.71	0.45	0.71	0.40
p-values [b]	0.008	0.012	0.006	0.037	0.158	0.398

[a] Treatments were processed with kernel processor (KP) and processed through experimental processor once or twice (1X and 2X, respectively). [b] Standard error of the mean. Within each column, lower case markers indicate significant differences at $p < 0.05$ using Tukey's comparisons.

4. Discussion

The physical effect of processing WPC is often only quantified by whole-plant particle size or Corn Silage Processing Score (CSPS). Neither metric adequately describes the physical effect of processing on the fiber fraction. Because of the absence of grain, the particle size of the plants without ears was two to three times larger than the whole-plant particle size (Table 3). This shows that whole-plant particle size as determined by screening does not adequately describe the fiber fraction. The processing level index (PLI) as used here was a better way to quantify the physical disruption caused by processing. For instance, there was only a 4 mm difference in average whole-plant particle size between the KP and 1X treatments (Table 3), yet the PLI was 19 percentage points greater for the latter treatment (Table 2). This was due to the increased surface area and cell rupture caused by impact–shredding processing. By contrast, the average whole-plant particle size was 18 mm smaller for the KP treatment compared to the UP treatment, but here, the PLI was only 5 percentage points greater. These results show that unlike impact–shredding processing, conventional roll processing as currently practiced does little to change the physical form of the fiber fraction and that that the PLI does a better job of quantifying plant physical disruption than particle size alone. Future research on processing WPC should include the processing level index, or a similar metric, as a means to quantify the physical effect of processing on both the grain and fiber fractions.

Dairy cattle diets containing of finely chopped forages and high levels of grain may not contain adequate particle size to maintain proper rumen function and prevent certain metabolic disorders [22]. It has been suggested that the fraction of total screened material residing on or above an 8 mm screen is a useful metric to describe the physical effectiveness of the fiber and the rumination potential of that feed [22]. The average particle size of the plants processed without ears was 26, 22, and 11 mm for the KP, 1X, and 2X treatments and the fraction of mass on or above the 6.4 mm screen was 60%, 51%, and 34%, respectively (Table 3). Although the particle size metrics of the KP and 1X treatments were similar, the latter treatment had greater rapidly soluble fraction and greater DM disappearance through the first 7 h of incubation (Figure 5 and Table 8). This can be attributed to the physical disruption of the grain and fiber fractions caused by impact–shredding processing as quantified by the PLI (36% KP vs. 54% 1X). The 2X treatment produced the best in situ digestion performance, but the particle size and fraction on or above the 6.4 mm screen were much smaller than the control KP treatment. Increasing the chop length from 50 to 100 mm (Exp. 7) did little to improve the whole-plant particle size (Table 3). Whether these particle size concerns translate into rumination or metabolic issues is an important next step for future research into animal response to WPC subjected to intensive mechanical processing.

It was observed that processing shredded the stalk into strands of fibers and destroyed the tubular structure of the stalk (Figure 2). This subsequently made the bulk material more compliant, which resulted in a greater compacted density (Figure 4). The 1X and 2X treatments had significantly smaller whole-plant and kernel particle size (Tables 3 and 4), which also contributed to improved void reduction and consolidation. Muck and Holmes [23] suggested that the compacted dry basis density in bunk or bag silos should be at least 240 kg·m^{-3} to minimize DM losses in bunk or bag silos. Only the 1X or 2X treatments were able to achieve this target density at the pressures applied. Grass or alfalfa silage processed by shredding had greater density in laboratory-scale silos [24] or wrapped bales [25], but to date, there has been no published results on how intensive processing affects silage density in a bag or bunk silos. When a chop length of 100 mm was used prior to processing (Exp. 7), the compact density was 9% to 13% greater compared to KP material using a 25 mm chop length. This suggests that chopping using a very long chop length prior to processing with the impact–shredding processor may not have a detrimental effect on silage density. Further research is needed to determine if WPC processed with the impact–shredding processor will result in greater density in bag or bunk silos.

The energy requirements for processing with the impact–shredding processor was greater than that reported for conventional roll-type kernel processors. Energy requirements for processing WPC chopped at 19 mm chop length and processed with a conventional set of kernel processing rolls was between 0.6 and 1.1 kW-h·Mg^{-1} [26]. Energy requirements for shredding unchopped corn using a pair of kernel processing rolls ranged from 0.9 to 1.9 kW-h·Mg^{-1} and averaged 1.3 kW-h·Mg^{-1} [27]. Because a harvester's overall energy requirements impact its throughput capacity, energy requirement, and machine cost, the energy requirements of processing are an important factor in the cost–benefit consideration of the impact–shredding process. When the processor was operated at 51 and 65 m·s^{-1}, the resulting PLI were statistically similar, but the energy requirements were 32% less at the slower rotor speed (Table 5). Processing with the experimental processor produced numerically similar physical properties when processing material chopped at either 50 or 100 mm chop length (Tables 2–4). Chopping at longer chop length would save energy expended at the harvester's cutterhead, partially offsetting the added power requirement of the impact–shredding processor. Previous work has established that increasing the chop length for WPC from 9.5 to 19 mm reduced the whole-machine energy requirements by 20% to 44% [26,28]. Further research is needed to understand the impact of processing longer material and to parse the energy requirements of chopping and processing on a forage harvester that combines conventional chopping and processing with an impact–shredding processor.

An alternative to processing WPC at harvest is to process post-ensiling. Processing by impact and shredding was effective at altering WPC physical properties when applied either pre- or post-ensiling (Table 6). Due to high energy requirements, processing in this manner at harvest might reduce achievable harvest rates or necessitate a more powerful engine to maintain current harvest rates. If processing took place post-ensiling, it could diminish the required severity of kernel processing at harvest as currently practiced using conventional kernel processors, increasing harvest productivity and timeliness. However, post-ensiling processing would eliminate the potential benefits from greater storage density and require an added step during feed preparation.

Processing WPC with conventional kernel processors has consistently shown to improve ruminant starch digestion [2,29], but achieving optimum CSPS of 70% is challenging [3,30]. The reported impact of processing on WPC fiber digestion has been variable, with both declines [5,9,10] and increases reported [8]. Compared to conventional kernel processing, Jančík et al. [31] reported more intensive processing with an on-board kernel processor increased 12 h DM disappearance, but the difference was only 2 percentage points. WPC processed with a conventional kernel processor had more rapid attachment and heavier colonization of rumen bacteria compared with the unprocessed silage, which enhanced ruminal digestion and fermentation [32]. However, the effect was more pronounced for the kernels than for the stems. Processing with a conventional kernel processor improved the rapidly soluble DM by 3.9 percentage points and the 8 h in situ DM disappearance by 2.1 percentage points [10]. By contrast, in this research the rapidly soluble DM increased by 10.2 percentage points and the 7 h in situ DM disappearance was 5.0 percentage points greater for the 2X treatment than for the KP treatment (Table 8). Processing WPC with a screenless hammermill as investigated here produced material that was highly fiberized (Figure 2), resulting in consistently greater processing level index (Table 2), which was the result of greater specific surface area and cell rupture of the fiber fraction. Processing pulverized the kernel fraction such that CSPS was 86% and 95% for the 1X and 2X treatments, respectively (Table 7). Although there were some differences in composition and fermentation properties (Table 7), these differences were small and not likely to be biologically significant. Therefore, it can be concluded that the quantified physical differences were responsible for the observed increase in rapidly soluble DM and DM disappearance for the impact-shredded treatments.

Improved DM disappearance was likely the result of greater processing of both the fiber and starch fractions, but the DM disappearance of these fractions was not observed separately in this work. Previous research has shown that greater CSPS increased starch digestion [3]. The high CSPS of the 1X and 2X treatments (Table 7) may have led to greater starch digestion than the KP treatment. There has been no published research covering the digestion of highly fiberized corn plants as produced in this research. Because decreased fiber digestibility has been linked to greater starch digestibility [5,33], new research is needed to draw conclusions regarding how processing WPC by impact–shredding affects the relative changes in digestion of the starch and fiber fractions. An equally important next step is to determine how feeding WPC processed by impact and shredding affects dairy cattle lactation performance.

Based on an exhaustive review of the literature, it has been suggested that further technological improvement of processors is warranted to allow for more consistent processing of WPC [34]. The results of this research show that processing by impact and shredding is a new approach to change the physical form of both the grain and fiber fraction of WPC.

5. Conclusions

Processing whole-plant corn by impact and shredding met the objective of creating greater physical disruption of both the fiber and grain fractions compared to conventional processing rolls on a forage harvester. The objective of improving DM digestion in lactating dairy cows was also met by processing in the manner investigated. Potential concerns with this process include maintaining fiber length and the energy requirements for processing. An important next step is to design a mechanism that achieves the desired processing level in a single operation. A feeding trial should be considered to determine lactating dairy cow performance when fed material processed by impact and shredding.

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